WILEY VISUALIZING™ | NATIONAL GEOGRAPHIC

VISUALIZING HUMAN BIOLOGY

THIRD EDITION

KATHLEEN A. IRELAND

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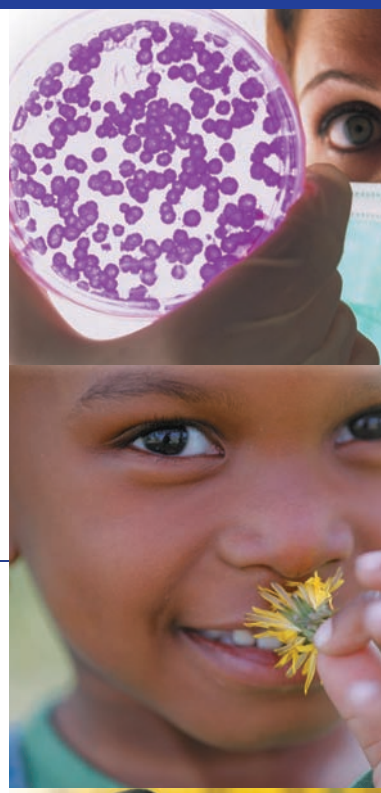
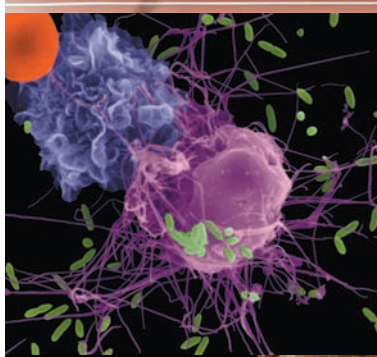
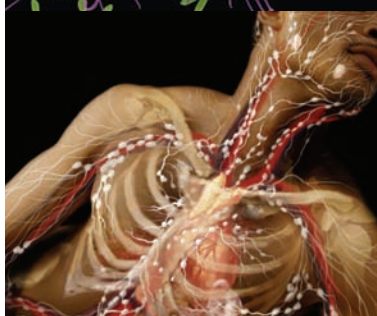
KATHLEEN ANNE IRELAND, PH.D.







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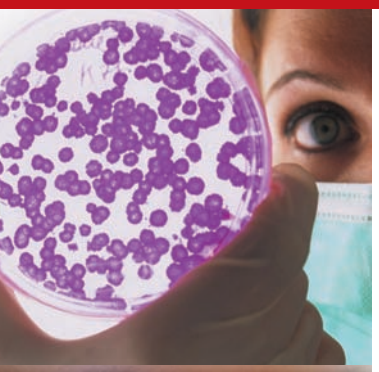


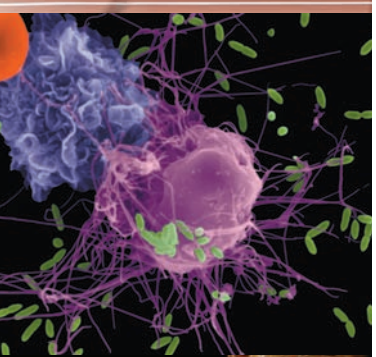
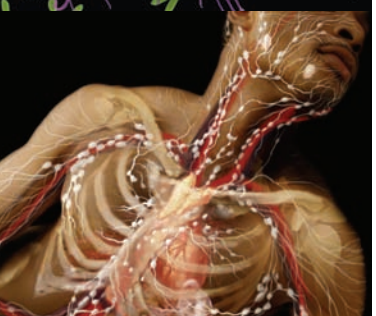

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How Is Wiley Visualizing Different?

Wiley Visualizing differs from competing textbooks by uniquely combining three powerful elements: a visual pedagogy integrated with comprehensive text, the use of authentic situations and issues from the National Geographic Society collections, and the inclusion of interactive multimedia in the *WileyPLUS* learning environment. Together these elements deliver a level of rigor in ways that maximizes student learning and involvement. Each key concept and its supporting details have been analyzed and carefully crafted to maximize student learning and engagement.

(1) Visual Pedagogy. Wiley Visualizing is based on decades of research on the use of visuals in learning.[1] Using the cognitive theory of multimedia learning, which is backed up by hundreds of empirical research studies, Wiley's authors select visualizations for their texts that specifically support students' thinking and learning—for example, the selection of relevant materials, the organization of the new information, or the integration of the new knowledge with prior knowledge. Visuals and text are conceived and planned together in ways that clarify and reinforce major concepts while allowing students to understand the details. This commitment to distinctive and consistent visual pedagogy sets Wiley Visualizing apart from other textbooks.

(2) Authentic Situations and Problems. Through Wiley's exclusive publishing partnership with National Geographic, *Visualizing Human Biology, Third Edition* has benefited from National Geographic's more than century-long recording of the world and offers an array of remarkable photographs, maps, media, and film from the National Geographic Society collections. These authentic materials immerse the student in real-life issues in environmental science, thereby enhancing motivation, learning, and retention.[2] These authentic situations, using high-quality materials from the National Geographic Society collections, are unique to Wiley Visualizing.

(3) Interactive Multimedia. Wiley Visualizing is based on the understanding that learning is an active process of knowledge construction. *Visualizing Human Biology, Third Edition is* therefore tightly integrated with *WileyPLUS*, our online learning environment that provides interactive multimedia activities in which learners can actively engage with the materials. The combination of textbook and *WileyPLUS* provides learners with multiple entry points to the content, giving them greater opportunity to explore concepts, interact with the material, and assess their understanding as they progress through the course. Wiley Visualizing makes this online *WileyPLUS* component a key element of the learning and problem-solving experience, which sets it apart from other textbooks whose online component is a mere drill-and-practice feature.

Wiley Visualizing and the *WileyPLUS* Learning Environment are designed as a natural extension of how we learn

Visuals, comprehensive text, and learning aids are integrated to display facts, concepts, processes, and principles more effectively than words alone can. To understand why the visualizing approach is effective, it is first helpful to understand how we learn.

1. Our brain processes information using two channels: visual and verbal. *Our working memory* holds information that our minds process as we learn. In working memory we begin to make sense of words and pictures, and build verbal and visual models of the information.
2. When the verbal and visual models of corresponding information are connected in working memory, we form more comprehensive, or integrated, mental models.
3. When we link these integrated mental models to our prior knowledge, which is stored in our *long-term memory*, we build even stronger mental models. When an integrated mental model is formed and stored in long-term memory, real learning begins.

The effort our brains put forth to make sense of instructional information is called *cognitive load*. There are two kinds of cognitive load: productive cognitive load, such as when we're engaged in learning or exert positive effort to create mental models; and unproductive cognitive load, which occurs when the brain is trying to make sense of needlessly complex content or when information is not presented well. The learning process can be impaired when the amount of information to be processed exceeds the capacity of working memory. Well-designed visuals and text with effective pedagogical guidance can reduce the unproductive cognitive load in our working memory.

[1] Mayer, R.E. (Ed.) 2005. *The Cambridge Handbook of Multimedia Learning.* New York: Cambridge University Press.
[2] Donovan, M. S., and J. Bransford, (Eds.) 2005. *How Students Learn: Science in the Classroom*. The National Academy Press. Available at http://www.nap.edu/openbook.php?record_id=11102&page=1

Wiley Visualizing is designed for engaging and effective learning

The visuals and text in *Visualizing Human Biology, Third Edition* are specially integrated to present complex processes in clear steps and with clear representations, organize related pieces of information, and integrate related information with one another. This approach, along with the use of interactive multimedia, minimizes unproductive cognitive load and helps students engage with the content. When students are engaged, they're reading and learning, which can lead to greater knowledge and academic success.

Research shows that well-designed visuals, integrated with comprehensive text, can improve the efficiency with which a learner processes information. In this regard, SEG Research, an independent research firm, conducted a national, multisite study evaluating the effectiveness of Wiley Visualizing. Its findings indicate that students using Wiley Visualizing products (both print and multimedia) were more engaged in the course, exhibited greater retention throughout the course, and made significantly greater gains in content area knowledge and skills, as compared to students in similar classes that did not use Wiley Visualizing.[3]

The use of *WileyPLUS* can also increase learning. According to a white paper titled "Leveraging Blended Learning for More Effective Course Management and Enhanced Student Outcomes" by Peggy Wyllie of Evince Market Research & Communications[4], studies show that effective use of online resources can increase learning outcomes. Pairing supportive online resources with face-to-face instruction can help students to learn and reflect on material, and deploying multimodal learning methods can help students to engage with the material and retain their acquired knowledge. *WileyPLUS* provides students with an environment that stimulates active learning and enables them to optimize the time they spend on their coursework. Continual assessment/remediation is also key to helping students stay on track. The *WileyPLUS* system facilitates instructors' course planning, organization, and delivery and provides a range of flexible tools for easy design and deployment of activities and tracking of student progress for each learning objective.

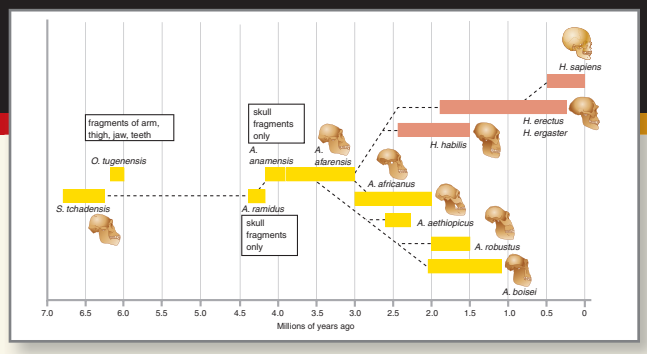
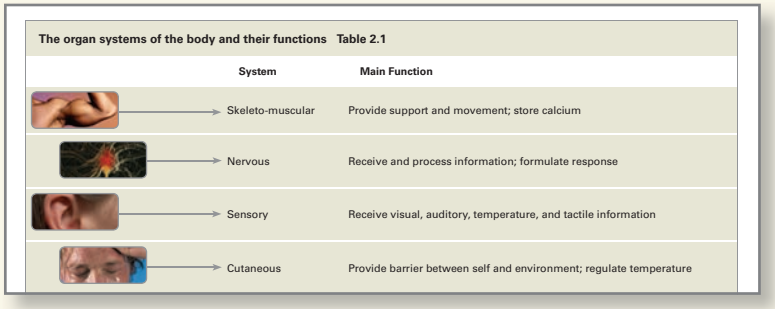


Figure 1: A closer look at the human family tree This timeline visually organizes information to integrate related events and time periods pictorially.



The organ systems of the body and their functions Table 2.1

System	Main Function
Skeleto-muscular	Provide support and movement; store calcium
Nervous	Receive and process information; formulate response
Sensory	Receive visual, auditory, temperature, and tactile information
Cutaneous	Provide barrier between self and environment; regulate temperature

Figure 2: The organ systems of the body and their functions This matrix visually organizes information to reduce cognitive load.

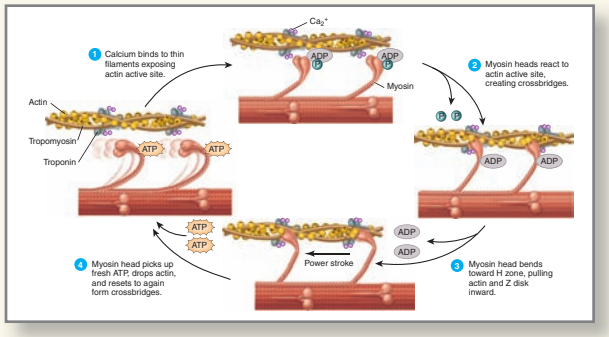


Figure 3: Muscle contraction cycle Textual elements have been physically integrated with the visual elements. This eliminates split attention (dividing our attention between several sources of different information). The arrows visually display processes, easing the way we recognize relationships.

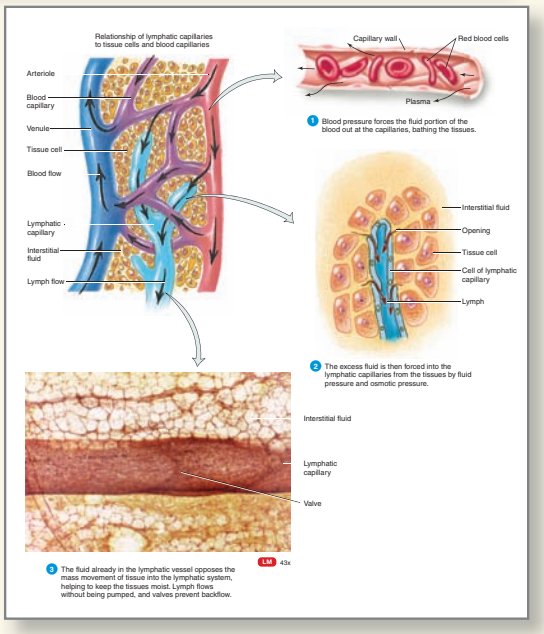


Figure 4: Lymphatic flow This illustration steps the student through increasing levels of depth and complexity to provide a multifaceted view into key topics.

[3] SEG Research. 2009. Improving Student-Learning with Graphically-Enhanced Textbooks: A Study of the Effectiveness of the Wiley Visualizing Series. Available online at www.segmeasurement.com.

[4] Peggy Wyllie. 2009. Leveraging Blended Learning for More Effective Course Management and Enhanced Student Outcomes. Available online at http://catalog.wiley-plus.com./about/instructors/whitepaper.html.

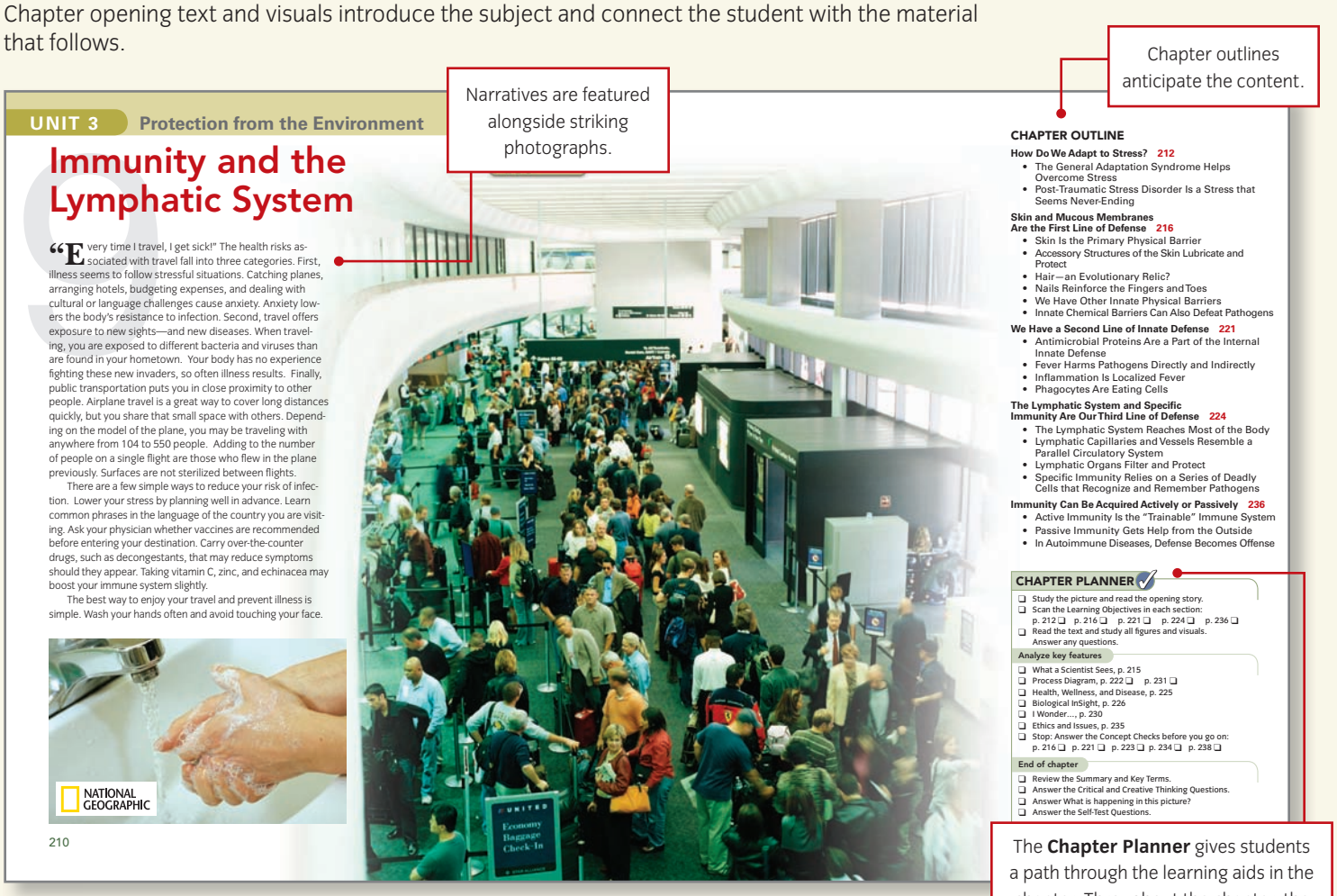
How Are the Wiley Visualizing Chapters Organized?

Student engagement requires more than just providing visuals, text, and interactivity—it entails motivating students to learn. Student engagement can be behavioral, cognitive, social, and/or emotional. It is easy to get bored or lose focus when presented with large amounts of information, and it is easy to lose motivation when the relevance of the information is unclear. Wiley Visualizing and *WileyPLUS* work together to reorganize course content into manageable learning objectives and relate it to everyday life. The design of *WileyPLUS* is based on cognitive science, instructional design, and extensive research into user experience. It transforms learning into an interactive, engaging, and outcomes-oriented experience for students.

The content in Wiley Visualizing and *WileyPLUS* is organized in learning modules. Each module has a clear instructional objective, one or more examples, and an opportunity for assessment. These modules are the building blocks of Wiley Visualizing.

Each Wiley Visualizing chapter engages students from the start

Chapter opening text and visuals introduce the subject and connect the student with the material that follows.

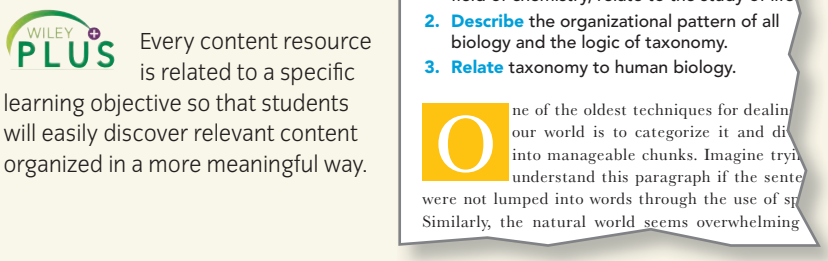


Experience the chapter through a *WileyPLUS* course. The content through *WileyPLUS* transports the student into a rich world of online experience that can be personalized, customized, and extended. Students can create a personal study plan to help prioritize which concepts to learn first and to focus on weak points.

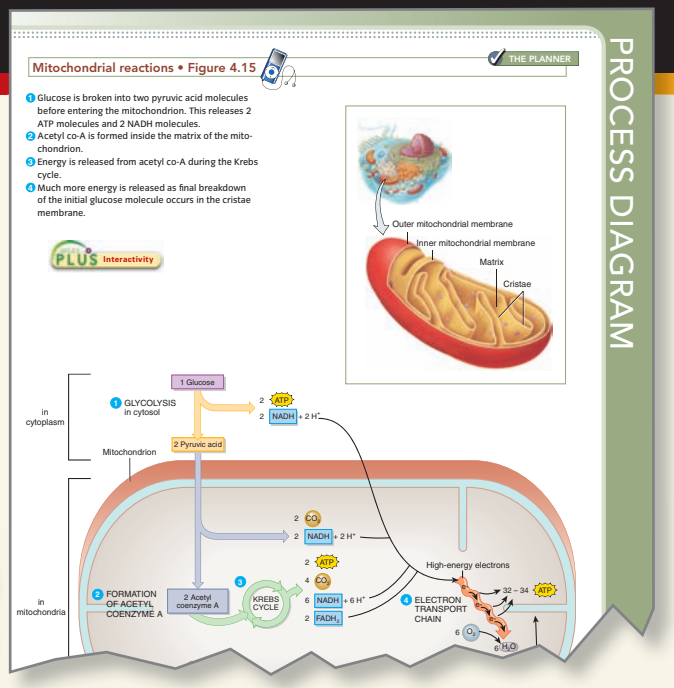
Wiley Visualizing media guides students through the chapter

Wiley Visualizing in *WileyPLUS* gives students a variety of ways to approach their study—through text, visuals, illustrations, interactions, and assessments—that work together to provide students with a guided path through the content. But this path isn't static—it can be personalized, customized, and extended to suit individual needs, and so it offers students flexibility as to how they want to study and learn the content

Learning Objectives at the start of each section indicate in behavioral terms the concepts that students are expected to master while reading the section.



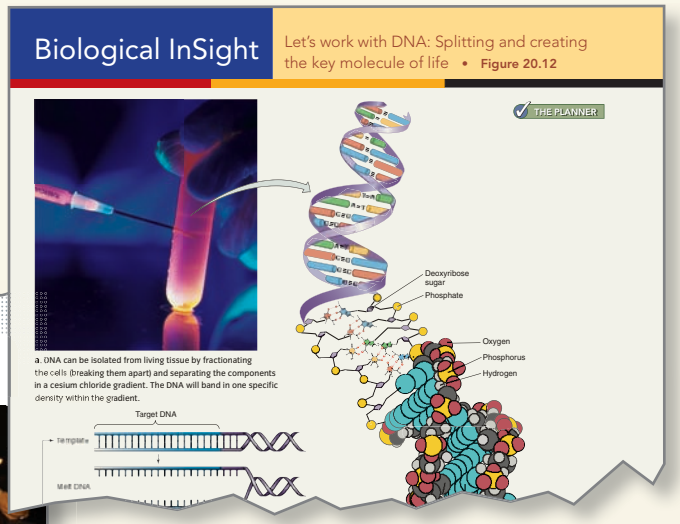
WILEY PLUS Every content resource is related to a specific learning objective so that students will easily discover relevant content organized in a more meaningful way.



Process Diagrams provide in-depth coverage of processes correlated with clear, step-by-step narrative, enabling students to grasp important topics with less effort.

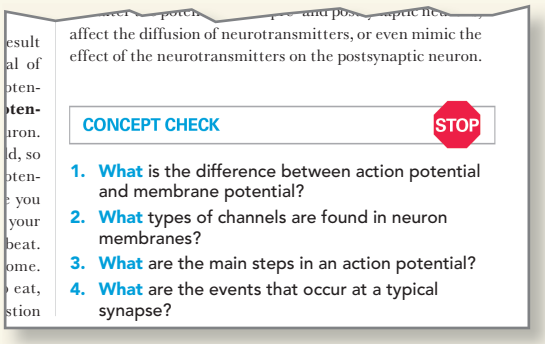
WILEY PLUS Interactivity **Interactive Process Diagrams** provide additional visual examples and descriptive narration of a difficult concept, process, or theory, allowing the students to interact with the content. Many of these diagrams are built around a specific feature such as a Process Diagram. Look for them in *WileyPLUS* when you see this icon.

Biological InSight features are multipart visual sections that focus on a key concept or topic in the chapter, exploring it in detail or in broader context using a combination of photos, figures, and data.



Think Critically questions let students analyze the material and develop insights into essential concepts.

What a Scientist Sees highlights a concept or phenomenon that would stand out to a professional in the field. Photos and figures are used to compare how a nonscientist and a scientist see the issues, and students apply their observational skills to answer questions.



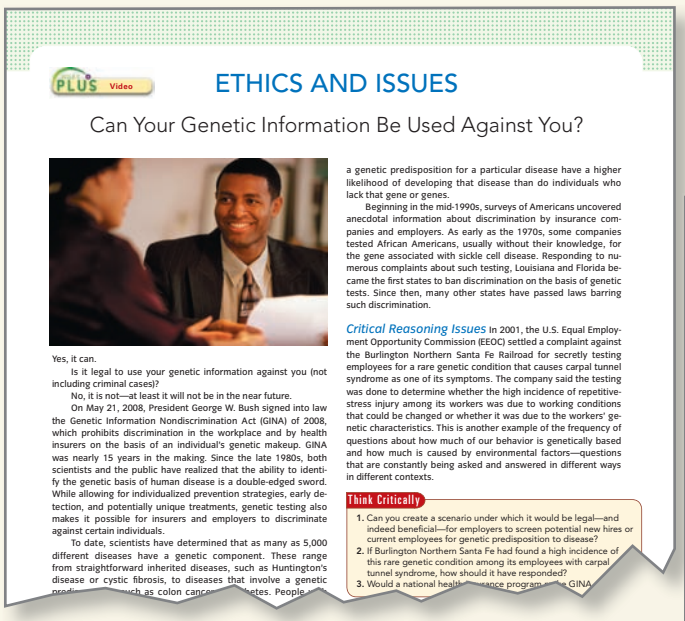
affect the diffusion of neurotransmitters, or even mimic the effect of the neurotransmitters on the postsynaptic neuron.

CONCEPT CHECK STOP

1. **What** is the difference between action potential and membrane potential?
2. **What** types of channels are found in neuron membranes?
3. **What** are the main steps in an action potential?
4. **What** are the events that occur at a typical synapse?

Concept Check questions at the end of each section allow students to test their comprehension of the learning objectives.

WILEY PLUS At the end of each learning objective module, students can assess their progress with independent practice opportunities and quizzes. This feature gives them the ability to gauge their comprehension and grasp of the material. Practice tests and quizzes help students self-monitor and prepare for graded course assessments.



WILEY PLUS Video

ETHICS AND ISSUES

Can Your Genetic Information Be Used Against You?

Yes, it can.

Is it legal to use your genetic information against you (not including criminal cases)?

No, it is not—at least it will not be in the near future.

On May 21, 2008, President George W. Bush signed into law the Genetic Information Nondiscrimination Act (GINA) of 2008, which prohibits discrimination in the workplace and by health insurers on the basis of an individual's genetic makeup. GINA was nearly 15 years in the making. Since the late 1980s, both scientists and the public have realized that the ability to identify the genetic basis of human disease is a double-edged sword. While allowing for individualized prevention strategies, early detection, and potentially unique treatments, genetic testing also makes it possible for insurers and employers to discriminate against certain individuals.

To date, scientists have determined that as many as 5,000 different diseases have a genetic component. These range from straightforward inherited diseases, such as Huntington's disease or cystic fibrosis, to diseases that involve a genetic predisposition, such as colon cancer and diabetes. People with a genetic predisposition for a particular disease have a higher likelihood of developing that disease than do individuals who lack that gene or genes.

Beginning in the mid-1990s, surveys of Americans uncovered anecdotal information about discrimination by insurance companies and employers. As early as the 1970s, some companies tested African Americans, usually without their knowledge, for the gene associated with sickle cell disease. Responding to numerous complaints about such testing, Louisiana and Florida became the first states to ban discrimination on the basis of genetic tests. Since then, many other states have passed laws barring such discrimination.

Critical Reasoning Issues In 2001, the U.S. Equal Employment Opportunity Commission (EEOC) settled a complaint against the Burlington Northern Santa Fe Railroad for secretly testing employees for a rare genetic condition that causes carpal tunnel syndrome as one of its symptoms. The company said the testing was done to determine whether the high incidence of repetitive-stress injury among its workers was due to working conditions that could be changed or whether it was due to the workers' genetic characteristics. This is another example of the frequency of questions about how much of our behavior is genetically based and how much is caused by environmental factors—questions that are constantly being asked and answered in different ways in different contexts.

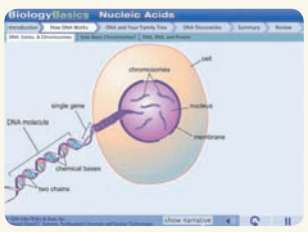
Think Critically

1. Can you create a scenario under which it would be legal—and indeed beneficial—for employers to screen potential new hires or current employees for genetic predisposition to disease?
2. If Burlington Northern Santa Fe had found a high incidence of this rare genetic condition among its employees with carpal tunnel syndrome, how should it have responded?
3. Would a national health insurance program like GINA

Ethics and Issues boxes explore the most pressing ethical and current events issues of our time. Through text and visuals, students connect human biology to issues they hear about every day.

BIOLOGY BASICS

Driven by instructor feedback about the most important topics for students to understand about biology, Biology Basics provides a suite of animated concepts and tutorials to give students a solid grounding in the key basic biology concepts when and where they need them.



Concepts ranging from scientific method to mitosis and meiosis are presented across modules in easy-to-understand language. Biology Basics is a great refresher for more advanced students or assistance for students to review the key concepts of biology.

I WONDER...

Is "Smart Water" Really a Smart Choice?

For years now, coaches have been telling athletes to drink water with added sugars and salts in order to prevent cramping and fatigue. As more adults participate in sports, beverage companies have begun to mass-produce sports drinks, marketing them in convenience stores and food stores. Are these more expensive, calorie-laden sports drinks really better than water? When we work out, we lose water and electrolytes through our sweat. The electrolytes we lose include sodium, potassium, calcium, and magnesium, as well as traces of zinc, iron, chromium, nickel, and lead. After strenuous activity, we feel dehydrated, with muscles that are fatigued and weak. Amazingly, some people lose up to three pounds of fluid an hour while exercising. This fluid must be replaced. In order to replace this, our thirst center triggers us to reach for a drink. Water will replace the volume lost, but will not add any electrolytes. Sports drinks that include sodium, potassium, and carbohydrates may in fact replenish our fluids more quickly. The salt in them will maintain that thirsty feeling, causing you to drink more than if you were drinking plain water. Also, the carbohydrates seem to maintain muscle strength more effectively than water alone. Dr. Larry Kenney, professor of physiology and kinesiology at Penn State University, suggests that sports drinks are a better choice if you have participated in athletics for over 45 minutes. "The longer the activity, the more important sports drinks become."

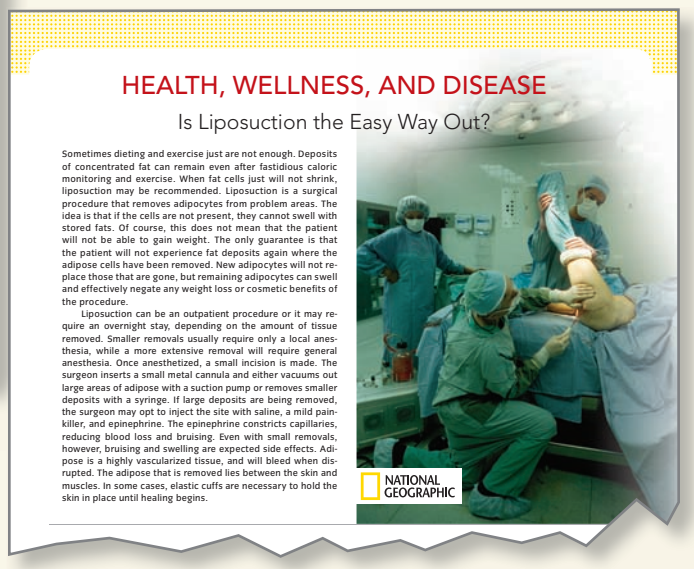
NATIONAL GEOGRAPHIC

the blood cannot filter into the nephron and therefore cannot be cleansed. Three criteria must be met in order to filter blood plasma through the glomerul

different life would be if we lost 180 liters of fluid every day! That is equal to 60 times the total plasma volume of th

I Wonder... are essays that explore common questions raised by students in human biology classes, assisting in student engagement and interest.

WILEY PLUS Video Students think critically and solve the problems of real-life situations with a rich collection of videos from a variety of sources, including over 28 **National Geographic videos** from their award-winning collection. Each video is linked to the text, and questions allow students to solve problems online. Videos are also available as lecture launcher PowerPoint presentations designed for in-class viewing and can be easily integrated into existing presentations.



HEALTH, WELLNESS, AND DISEASE

Is Liposuction the Easy Way Out?

Sometimes dieting and exercise just are not enough. Deposits of concentrated fat can remain even after fastidious caloric monitoring and exercise. When fat cells just will not shrink, liposuction may be recommended. Liposuction is a surgical procedure that removes adipocytes from problem areas. The idea is that if the cells are not present, they cannot swell with stored fats. Of course, this does not mean that the patient will not be able to gain weight. The only guarantee is that the patient will not experience fat deposits again where the adipose cells have been removed. New adipocytes will not replace those that are gone, but remaining adipocytes can swell and effectively negate any weight loss or cosmetic benefits of the procedure.

Liposuction can be an outpatient procedure or it may require an overnight stay, depending on the amount of tissue removed. Smaller removals usually require only a local anesthesia, while a more extensive removal will require general anesthesia. Once anesthetized, a small incision is made. The surgeon inserts a small metal cannula and either vacuums out large areas of adipose with a suction pump or removes smaller deposits with a syringe. If large deposits are being removed, the surgeon may opt to inject the site with saline, a mild painkiller, and epinephrine. The epinephrine constricts capillaries, reducing blood loss and bruising. Even with small removals, however, bruising and swelling are expected side effects. Adipose is a highly vascularized tissue, and will bleed when disrupted. The adipose that is removed lies between the skin and muscles. In some cases, elastic cuffs are necessary to hold the skin in place until healing begins.

NATIONAL GEOGRAPHIC

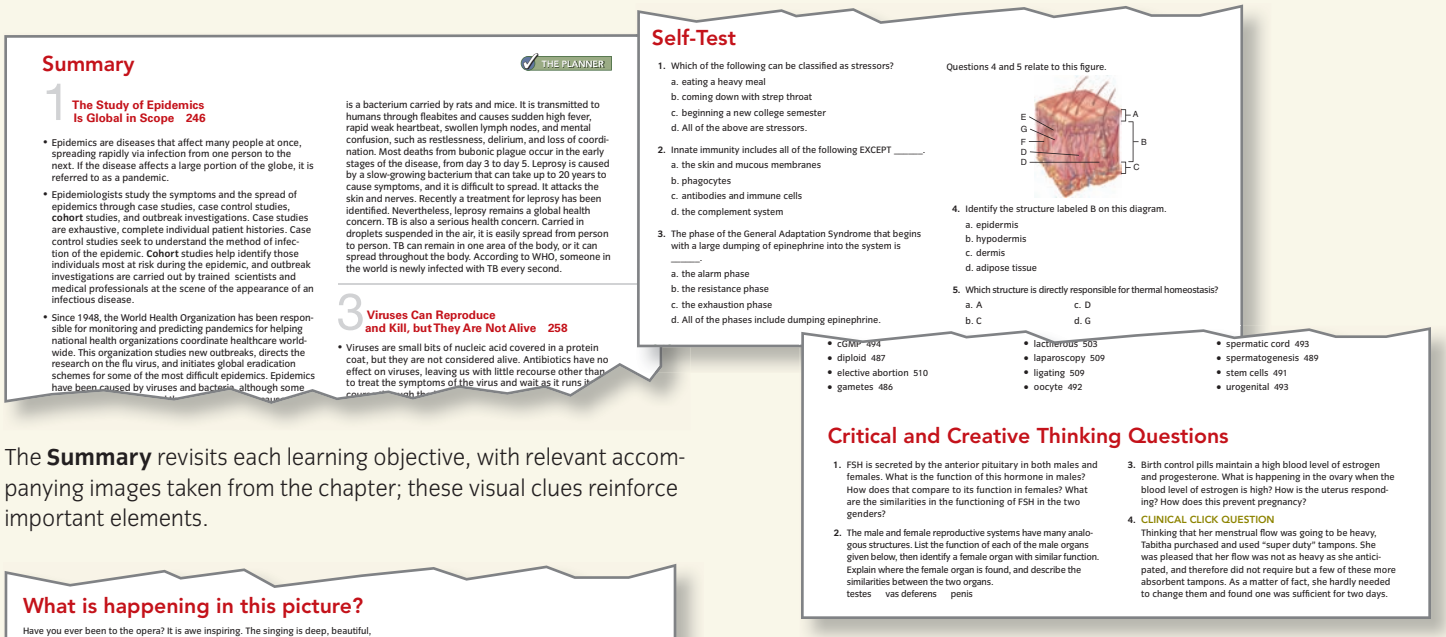
Health, Wellness, and Disease addresses clinical issues often discussed in the media. Students gain insight into the biological aspects of these topics as well as a basis for better decision making.

VISUAL PODCASTS

WILEY PLUS Written by Kathleen Ireland and designed around the figures in the text, these Podcasts provide audio narration coupled with visuals to drill into the core concepts of each chapter. Visual Podcasts are the perfect quick study tool for students right before they go in to the big test!

Student understanding is assessed at different levels

Wiley Visualizing with *WileyPLUS* offers students lots of practice material for assessing their understanding of each study objective. Students know exactly what they are getting out of each study session through immediate feedback and coaching.



Summary

THE PLANNER

1 The Study of Epidemics Is Global in Scope 246

- Epidemics are diseases that affect many people at once, spreading rapidly via infection from one person to the next. If the disease affects a large portion of the globe, it is referred to as a pandemic.
- Epidemiologists study the symptoms and the spread of epidemics through case studies, case control studies, **cohort** studies, and outbreak investigations. Case studies are exhaustive, complete individual patient histories. Case control studies seek to understand the method of infection of the epidemic. **Cohort** studies help identify those individuals most at risk during the epidemic, and outbreak investigations are carried out by trained scientists and medical professionals at the scene of the appearance of an infectious disease.
- Since 1948, the World Health Organization has been responsible for monitoring and predicting pandemics for helping national health organizations coordinate healthcare worldwide. This organization studies new outbreaks, directs the research on the flu virus, and initiates global eradication schemes for some of the most difficult epidemics. Epidemics have been caused by viruses and bacteria, although some

is a bacterium carried by rats and mice. It is transmitted to humans through fleabites and causes sudden high fever, rapid weak heartbeat, swollen lymph nodes, and mental confusion, such as restlessness, delirium, and loss of coordination. Most deaths from bubonic plague occur in the early stages of the disease, from day 3 to day 5. Leprosy is caused by a slow-growing bacterium that can take up to 20 years to cause symptoms, and it is difficult to spread. It attacks the skin and nerves. Recently a treatment for leprosy has been identified. Nevertheless, leprosy remains a global health concern. TB is also a serious health concern. Carried in droplets suspended in the air, it is easily spread from person to person. TB can remain in one area of the body, or it can spread throughout the body. According to WHO, someone in the world is newly infected with TB every second.

3 Viruses Can Reproduce and Kill, but They Are Not Alive 258

- Viruses are small bits of nucleic acid covered in a protein coat, but they are not considered alive. Antibiotics have no effect on viruses, leaving us with little recourse other than to treat the symptoms of the virus and wait as it runs its

Self-Test

1. Which of the following can be classified as stressors?
   a. eating a heavy meal
   b. coming down with strep throat
   c. beginning a new college semester
   d. All of the above are stressors.
2. Innate immunity includes all of the following EXCEPT _____.
   a. the skin and mucous membranes
   b. phagocytes
   c. antibodies and immune cells
   d. the complement system
3. The phase of the General Adaptation Syndrome that begins with a large dumping of epinephrine into the system is _____.
   a. the alarm phase
   b. the resistance phase
   c. the exhaustion phase
   d. All of the phases include dumping epinephrine.

Questions 4 and 5 relate to this figure.

4. Identify the structure labeled B on this diagram.
   a. epidermis
   b. hypodermis
   c. dermis
   d. adipose tissue
5. Which structure is directly responsible for thermal homeostasis?
   a. A c. D
   b. C d. G

- cGMP 494
- diploid 487
- elective abortion 510
- gametes 486
- lactiferous 503
- laparoscopy 509
- ligating 509
- oocyte 492
- spermatic cord 493
- spermatogenesis 489
- stem cells 491
- urogenital 493

Critical and Creative Thinking Questions

1. FSH is secreted by the anterior pituitary in both males and females. What is the function of this hormone in males? How does that compare to its function in females? What are the similarities in the functioning of FSH in the two genders?
2. The male and female reproductive systems have many analogous structures. List the function of each of the male organs given below, then identify a female organ with similar function. Explain where the female organ is found, and describe the similarities between the two organs.
   testes vas deferens penis
3. Birth control pills maintain a high blood level of estrogen and progesterone. What is happening in the ovary when the blood level of estrogen is high? How is the uterus responding? How does this prevent pregnancy?
4. CLINICAL CLICK QUESTION
   Thinking that her menstrual flow was going to be heavy, Tabitha purchased and used "super duty" tampons. She was pleased that her flow was not as heavy as she anticipated, and therefore did not require but a few of these more absorbent tampons. As a matter of fact, she hardly needed to change them and found one was sufficient for two days.

Critical and Creative Thinking Questions challenge students to think more broadly about chapter concepts. The level of these questions ranges from simple to advanced; they encourage students to think critically and develop an analytical understanding of the ideas discussed in the chapter.

What is happening in this picture?

Have you ever been to the opera? It is awe inspiring. The singing is deep, beautiful, controlled, and impressively loud. Although the opera singer's anatomy is basically the same as everyone else's, the sounds he or she is able to produce are far superior. Through years of training, the singer is able to control breathing rate, airflow, and laryngeal tension to produce incredible notes. The musical capability of our respiratory system is quite astounding.

Think Critically

1. What muscles are involved in the deep inhalations and controlled and prolonged exhalations necessary to sing like this?
2. Which portions of the larynx are involved in the control of pitch?
3. How would you expect the lung capacities of this person to compare with your own?

What is happening in this picture? presents an uncaptioned photograph that is relevant to a chapter topic and illustrates a situation students are not likely to have encountered previously. The photograph is paired with questions that ask the students to describe and explain what they can observe in the photo based on what they have learned.

Students can explore module topics further with customizable question sets that put the learning path in the hands of the instructor and student, promoting greater retention. The *WileyPLUS* Gradebook provides instant access to reports on trends in class performance, student use of course materials, and progress toward learning objectives, helping to inform decisions and to drive classroom discussions. Class section results can also be seen in graph form, making it easy to see how an individual is progressing in comparison to the rest of the class section. Students can also see their own progress instantly for each assignment listed according to the built-in calendar.

What Is the Organization of This Book?

Any course in human biology must introduce the student to science through a focus on the human being; the author and contributors achieve this by stressing the role of the human in the environment. This theme links together the broad-ranging information in any human biology course, providing an organizing principle that relates human biology to the students' daily experience, and gives them the stories behind the biology.

Each chapter begins with an intriguing vignette designed to stimulate a desire for more information. Throughout the chapter, students are further involved in the topics with the striking and stimulating photos and illustrations that demonstrate the concepts, questions, and stories behind the science in the *Health, Wellness, and Disease; Ethics and Issues*; and *I Wonder...* features. Tools and resources throughout the chapter help students check their understanding and focus on the most essential information. *Visualizing Human Biology, Third Edition* is further divided into five units to help students see how humans live, move, protect themselves, thrive, and populate our environment.

- *Unit 1* Introduction to the Study of Life, Chapters 1 through 5, lays the groundwork for creating understanding by focusing on the study of human life from the basic building blocks of the scientific method to cells and tissues.
- *Unit 2* Moving Through the Environment, Chapters 6, 7, and 8, investigates the human systems involved in movement: the skeletal, muscular, and nervous systems.
- *Unit 3* Protection from the Environment, Chapters 9, 10, and 11, describes how the integumentary and lymphatic systems protect the body against injury and invasion and includes two new chapters based on reviewer feedback: Chapter 10, Infectious Disease and Epidemiology and Chapter 11, Cancer.
- *Unit 4* Thriving within the Environment, Chapters 12, 13, 14, 15, and 16, explores how the cardiovascular and respiratory systems transport nutrients and oxygen to the tissues and how food is digested and wastes are eliminated.
- *Unit 5* Populating the Environment, Chapters 17, 18, 19, 20, and 21, covers the action of the endocrine system, which brings humans to sexual maturity, and the reproductive system. These final chapters on inheritance, DNA, evolution, and the ecological balance of the biosphere tie the entire book together.

New to this edition

The main focus of this third edition has been to stimulate critical thinking on the topics presented and to extend the usefulness of the art program beyond the printed page and keep the examples current and timely. Over half the introductory vignettes have been updated, keeping topics current and relevant for the student. Equally as many photos have been upgraded, and the material covered in the *Health, Wellness, and Disease; Ethics and Issues; and I Wonder...* boxes has been changed to reflect current topics in medicine, the media, and research. Based on reviewer response and student comments, 17 key illustrations have been reworked to include more data or to present a more visually appealing layout to be more useful for students and instructors. Additionally, data analysis questions are now included in at least one figure per chapter and the number of critical thinking questions has been increased, allowing the student to stop and really think about what is being represented in that figure or image. In order to provide even more information in the photos and illustrations presented, many more figures now include labels and captions explaining key features. In short, the art program is better than ever.

Critical thinking skills have been enhanced in this edition as well. At the end of the chapter, a new *Clinical Click* feature has been added to give students a chance to engage in more health and wellness–related issues. *Clinical Click* provides a short case study for the student to consider, relating the puzzle to the material in the chapter. A brief history is given, along with a Web site to visit for more information or to verify the diagnosis. Additionally, Think Critically questions to stimulate thought have been added to every *What a Scientist Sees* feature. These additions, along with the new Data Interpretation questions, provide many avenues for critical thought in each chapter.

Recognizing that everyone teaches this course just a little differently, instructor and student feedback have led to a number of improvements and changes. These include clarification of terminology in some cases, and a substantial reorganization of Chapter 18, The Reproductive Systems: Maintaining the Species. STDs now play a more prominent role in this discussion, while birth control is examined in a *Health, Wellness, and Disease* box.

In total, this edition presents much clearer, more thought-provoking information for students to engage with as they learn about human biology. The text, graphics, and imagery flow together to tell a compelling story that students will find enjoyable as well as informative.

Also available

Visualizing Human Biology Lab Manual by Jennifer Ellie of Wichita State University provides instructors and students with a lab book that focuses on engaging students in the study of human biology. Each lab includes **Active Learning Questions**, **Introductions, Exercises**, **Review Questions**, and **Visualizing the Lab**, a unique exercise that contains step-by-step instructions with accompanying pictures to help students successfully complete each lab assignment. *Visualizing Human Biology Lab Manual* is available as a stand-alone or in a customizable package with *Visualizing Human Biology* and your own materials, through the Wiley Custom Select program (www.customselect.wiley.com). Please contact your Wiley representative for more information.

How Does Wiley Visualizing Support Instructors?

Wiley Visualizing site

The Wiley Visualizing site hosts a wealth of information for instructors using Wiley Visualizing, including ways to maximize the visual approach in the classroom and a white paper titled "How Visuals Can Help Students Learn," by Matt Leavitt, instructional design consultant. You can also find information about our relationship with the National Geographic Society and other texts published in our program. Visit Wiley Visualizing at www.wiley.com/college/visualizing.

Wiley Custom Select

Wiley Custom Select gives you the freedom to build your course materials exactly the way you want them. Offer your students a cost-efficient alternative to traditional texts. In a simple three-step process, create a solution containing the content you want, in the sequence you want, delivered how you want. Visit Wiley Custom Select at http://customselect.wiley.com.

PowerPoint Presentations

(available in *WileyPLUS* and on the book companion site)

A complete set of highly visual PowerPoint presentations—one per chapter—by Bethany Marshall, Washington State University, is available online and in *WileyPLUS* to enhance classroom presentations. Tailored to the text's topical coverage and learning objectives, these presentations are designed to convey key text concepts, illustrated by embedded text art. Lecture Launcher PowerPoints also offer embedded links to videos to help introduce classroom discussions with short, engaging video clips.

Test Bank (available in *WileyPLUS* and on the book companion site)

The visuals from the textbook are also included in the Test Bank by Alicia Steinhart, West Valley College. The Test Bank has approximately 1,600 test items, with at least 25 percent of them incorporating visuals from the book. The test items include multiple-choice and essay questions testing a variety of comprehension levels. The test bank is available online in MS Word files, as a computerized Test Bank, and within *WileyPLUS*. The easy-to-use test-generation program fully supports graphics, print tests, student answer sheets, and answer keys. The software's advanced features allow you to produce an exam to your exact specifications.

Instructor's Manual

(available in *WileyPLUS* and on the book companion site)

For each chapter, materials by Keith Hench of Kirkwood Community College include Teaching Tips with illustrations, Lecture Launchers, and Discussion Questions to accompany the provided video, and Answers to Critical Thinking Questions.

Guidance is also provided on how to maximize the effectiveness of visuals in the classroom.

1. **Use visuals during class discussions or presentations.** Point out important information as the students look at the visuals, to help them integrate separate visual and verbal mental models.
2. **Use visuals for assignments and to assess learning.** For example, learners could be asked to identify samples of concepts portrayed in visuals.
3. **Use visuals to encourage group activities.** Students can study together, make sense of, discuss, hypothesize, or make decisions about the content. Students can work together to interpret and describe the diagram, or use the diagram to solve problems, conduct related research, or work through a case study activity.

4. **Use visuals during reviews.** Students can review key vocabulary, concepts, principles, processes, and relationships displayed visually. This recall helps link prior knowledge to new information in working memory, building integrated mental models.
5. **Use visuals for assignments and to assess learning.** For example, learners could be asked to identify samples of concepts portrayed in visuals.
6. **Use visuals to apply facts or concepts to realistic situations or examples.** For example, a familiar photograph, such as the Grand Canyon, can illustrate key information about the stratification of rock, linking this new concept to prior knowledge.

Image gallery

All photographs, figures, maps, and other visuals from the text are online and in *WileyPLUS* and can be used as you wish in the classroom. These online electronic files allow you to easily incorporate images into your PowerPoint presentations as you choose, or to create your own handouts.

Book Companion site

All instructor resources (the Test Bank, Instructor's Manual, PowerPoint presentations, and all textbook illustrations and photos in jpeg format) are housed on the book companion site (www.wiley.com/college/berg). Student resources include self quizzes and flashcards.

Wiley Faculty network

The Wiley Faculty Network (WFN) is a global community of faculty, connected by a passion for teaching and a drive to learn, share, and collaborate. Their mission is to promote the effective use of technology and enrich the teaching experience. Connect with the Wiley Faculty Network to collaborate with your colleagues, find a mentor, attend virtual and live events, and view a wealth of resources all designed to help you grow as an educator. Visit the Wiley Faculty Network at www.wherefacultyconnect.com.

How Has Wiley Visualizing Been Shaped by Contributors?

Wiley Visualizing and the *WileyPLUS* learning environment would not have come about without lots of people, each of whom played a part in sharing their research and contributing to this new approach. First and foremost, we begin with NGS.

National Geographic Society

Visualizing Human Biology, Third Edition offers an array of remarkable photographs, maps, illustrations, multimedia, and film from the National Geographic Society collections. Students using the book benefit from the rich, fascinating resources of National Geographic.

National Geographic School Publishing performed an invaluable service in fact-checking *Visualizing Human Biology, Third Edition.* They have verified every fact in the book with two outside sources, to ensure that the text is accurate and up-to-date. This kind of fact-checking is rare in textbooks and unheard of in most online media.

National Geographic Image Collection provided access to National Geographic's award-winning image and illustrations collection to identify the most appropriate and effective images and illustrations to accompany the content. Each image and illustration has been chosen to be instructive, supporting the processes of selecting, organizing, and integrating information, rather than being merely decorative.

National Geographic Digital Media TV enabled the use of National Geographic videos to accompany *Visualizing Human Biology, Third Edition* and enrich the text. Available for each chapter are video clips that illustrate and expand on a concept or topic to aid student understanding.

National Geographic Maps Group provided access to National Geographic's extensive map collection, along with new maps designed for the text by their team of cartographers.

Academic research consultants

Richard Mayer, Professor of Psychology, UC Santa Barbara. His cognitive theory of multimedia learning provided the basis on which we designed our program. He continues to provide guidance to our author and editorial teams on how to develop and implement strong, pedagogically effective visuals and use them in the classroom.

Jan L. Plass, Professor of Educational Communication and Technology in the Steinhardt School of Culture, Education, and Human Development at New York University. He co-directs the NYU Games for Learning Institute and is the founding director of the CREATE Consortium for Research and Evaluation of Advanced Technology in Education.

Matthew Leavitt, Instructional Design Consultant, advises the Visualizing team on the effective design and use of visuals in instruction and has made virtual and live presentations to university faculty around the country regarding effective design and use of instructional visuals.

Independent research studies

SEG Research, an independent research and assessment firm, conducted a national, multisite effectiveness study of students enrolled in entry-level college courses. The study was designed to evaluate the effectiveness of Wiley Visualizing**.** You can view the full research paper at www.wiley.com/college/visualizing/huffman/efficacy.html

Instructor and student contributions

Throughout the process of developing the concept of guided visual pedagogy for Wiley Visualizing, we benefited from the comments and constructive criticism provided by the instructors and colleagues listed below. We offer our sincere appreciation to these individuals for their helpful reviews and general feedback:

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Dedication

In deepest gratitude to my 100-year-old Nana, Elizabeth Propert Ireland, for all that she has taught me about strength, perseverance, and love; and as always, for my boys, Greg and Marc Tatum.

About the Author

Kathleen Ireland was born and raised on the East Coast of the United States and obtained her B.S. from the University of Alabama while gaining experience working both for a major pharmaceutical company in their basic research labs and for a Marine Sciences Foundation in Florida. She continued her education at the University of Alabama, earning an M.S. in Marine Sciences in 1981, studying aquatic ecology, and working for the Geological Survey of Alabama in strip mine reclamation. After a few years working for an agricultural genetics corporation and giving birth to two sons, Kathleen returned to school, earning a Ph.D. from Iowa State University while teaching their Human Biology course. She joined the faculty at ISU until moving to Maui for a position teaching human biology for the University of Hawaii, Maui Community College. She currently lives on Maui, where she surfs, participates in triathlons, and teaches biology and marine sciences at Seabury Hall. Kathleen is a member of Phi Kappa Phi, Golden Key, Alpha Gamma Delta, NSTA, HAPS, and AACE, where she serves on their editorial board. She regularly participates in AP exam readings and has been published as a media editor and contributing author on both anatomy and anatomy and physiology premedical textbooks. Most recently, she has received a 2008 Toyota Motor Corporation Institute of International Education Galápagos excursion, a 2009/2010 Toyota Tapestry large grant, and a multi-year HAIS/ HCF grant to enhance the schoolwide teaching of 21st century skills.

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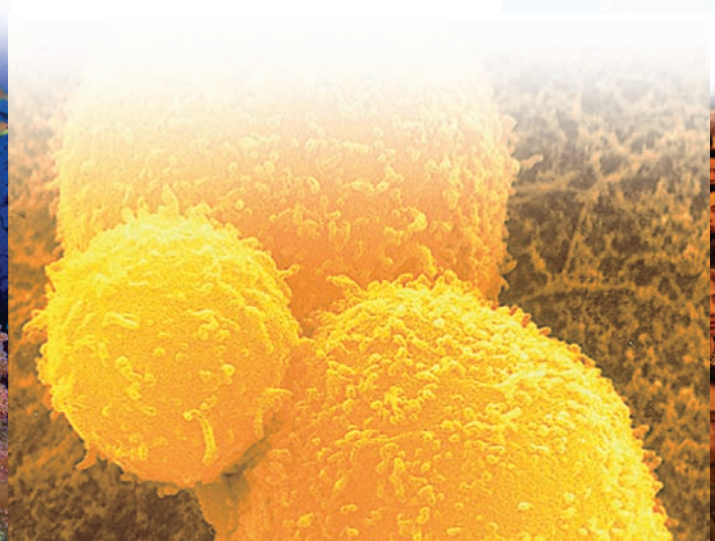

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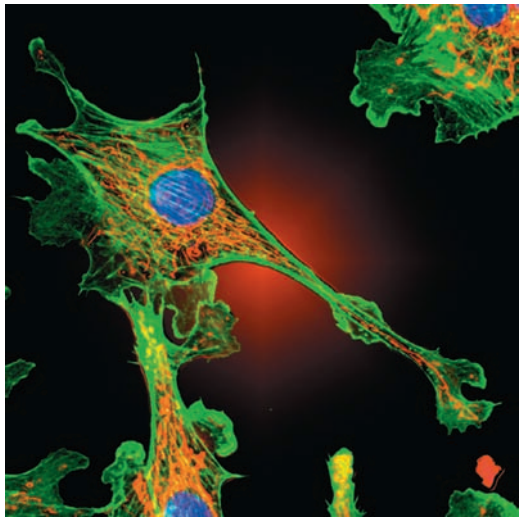

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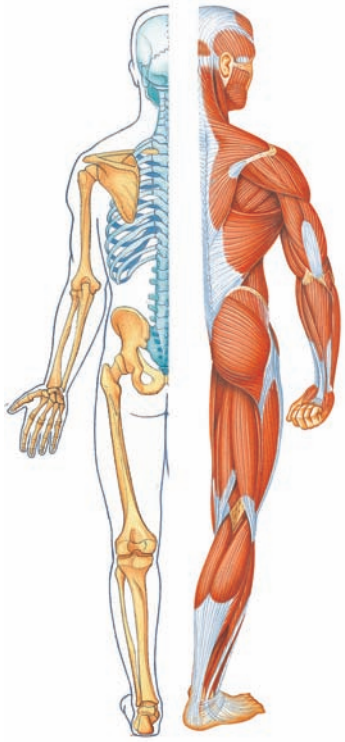

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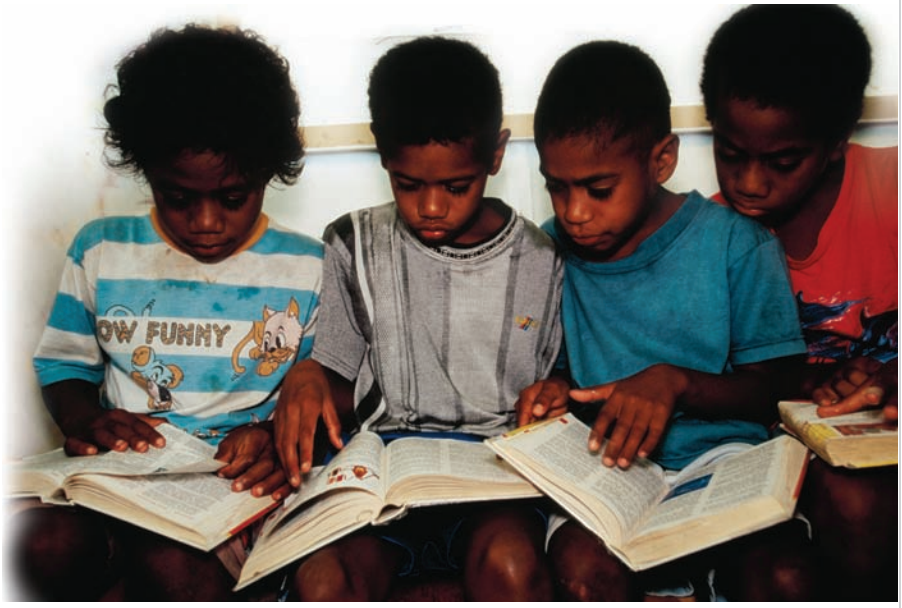

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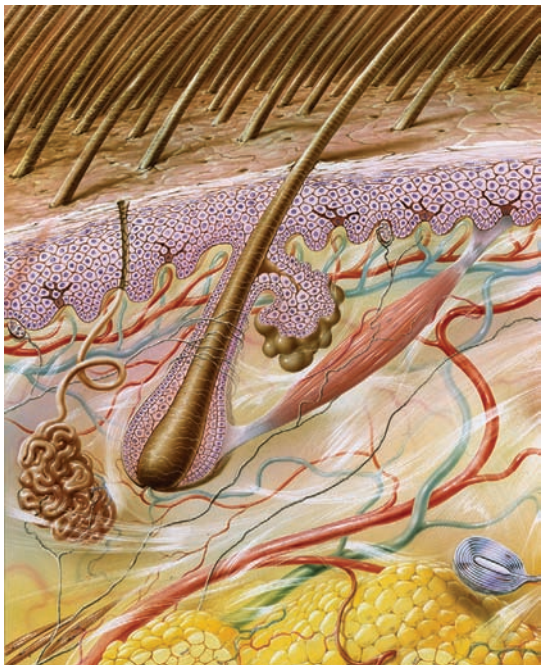

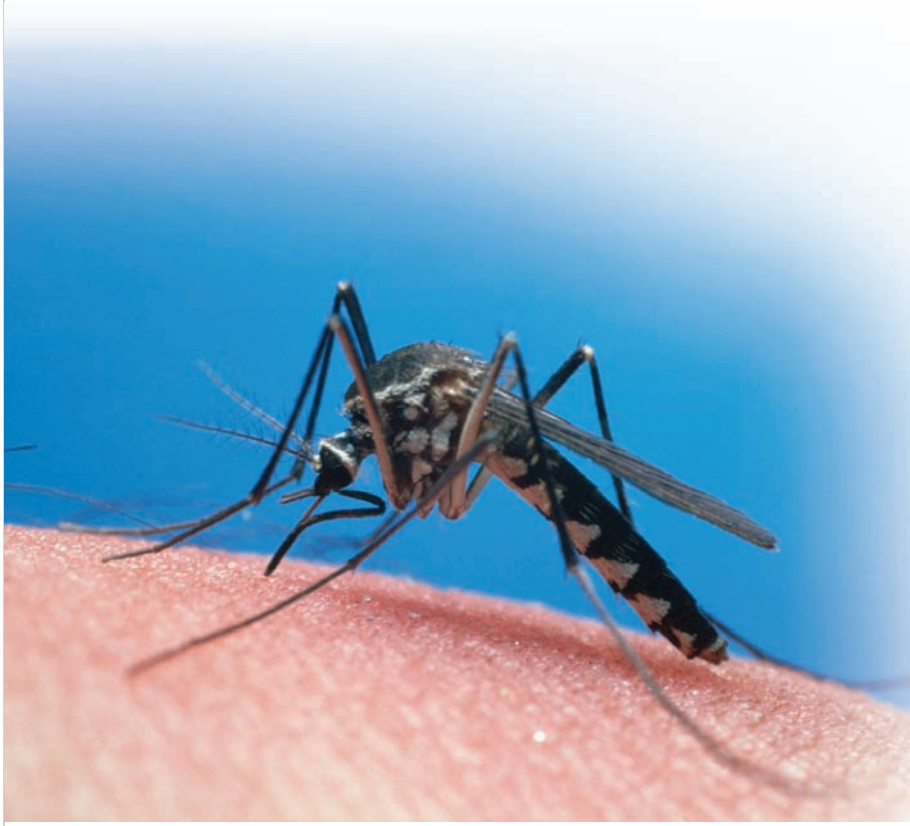

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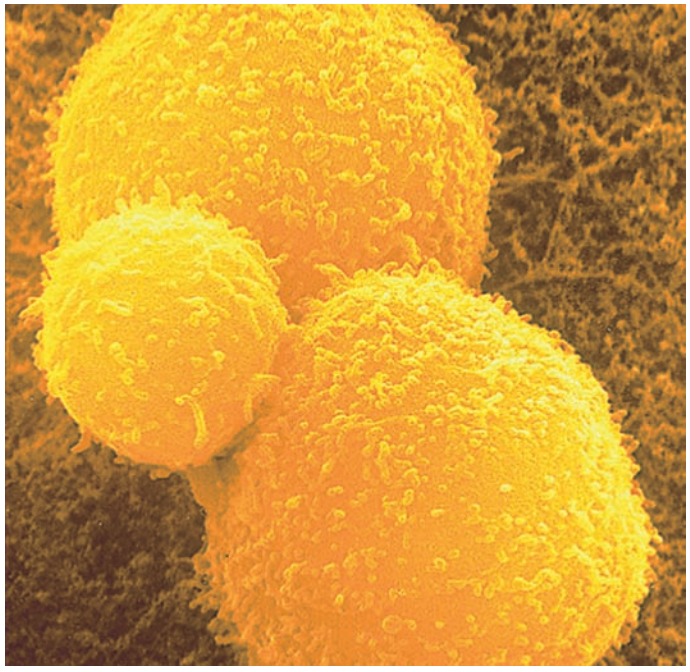

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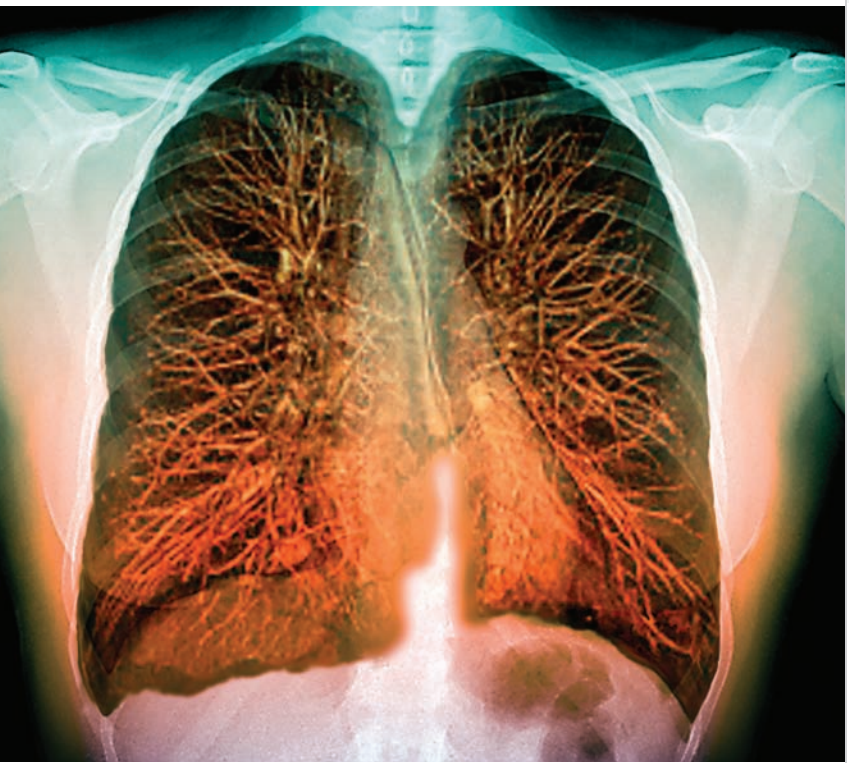

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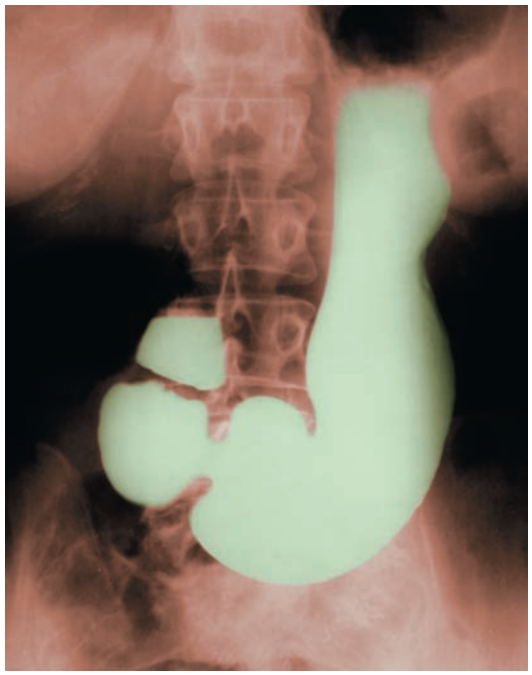

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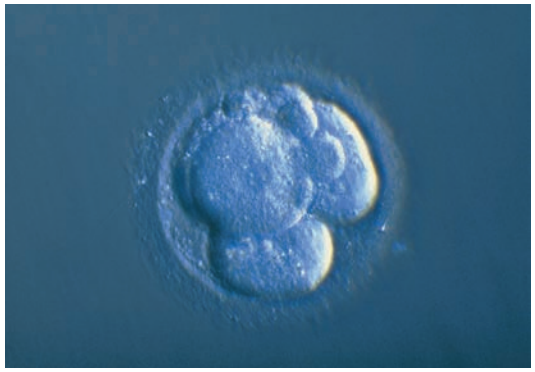

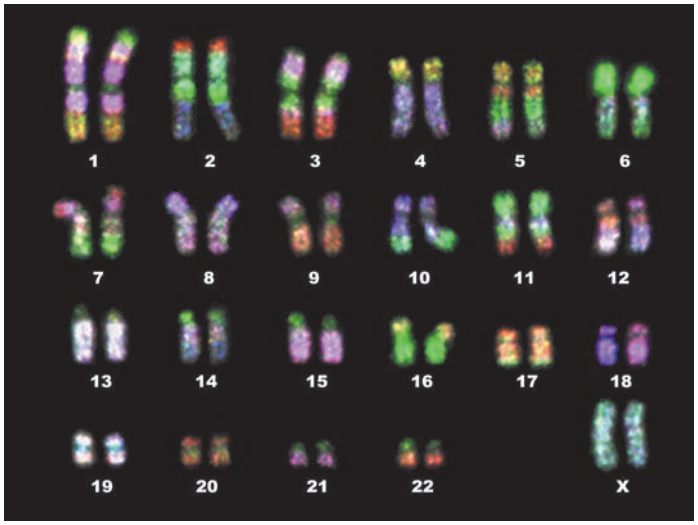

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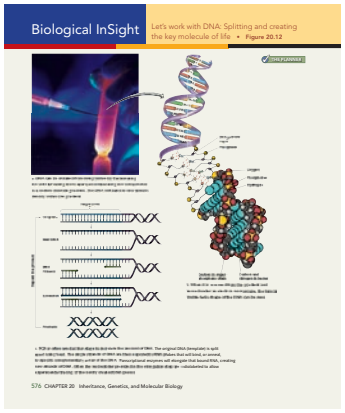

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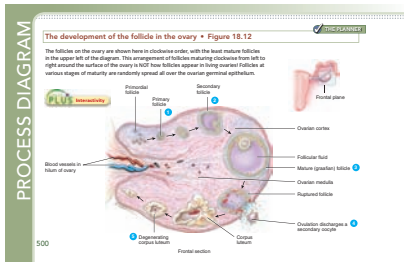
Process Diagram

These series or combinations of figures and photos describe and depict a complex process.



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1 What Is Life?

WILEY PLUS Video

Every day there is a new report on health and the human body. New over the counter products are advertised that claim to remove cellulite, erase wrinkles, banish acne, and whiten teeth. Television experts proclaim they can help you lose weight, gain muscular strength, increase your mental clarity, and boost your immune system by following their simple diet and exercise plan. Seemingly magical results are touted for a variety of new prescription drugs, while the list of side effects from those drugs grows exponentially. How can anyone make rational decisions about what to purchase, or even how to live, in light of all this information? Which of these claims makes sense, and which seem to have no basis in reality? Add to the bewildering array of health related advertisements the growing number of news stories about humans impacting the environment, and it is painfully obvious that living in the 21st century requires some specific knowledge. Today's consumer must have the ability to critically evaluate advertising claims, and make informed choices. The study of human biology is the perfect place to gain this understanding. Knowing what forms wrinkles allows you to evaluate products that claim to remove them. Being able to relate diet to cellular functioning is key to determining the effectiveness of new diet and exercise plans. Human biology can even supply the facts necessary to decide whether or not to vote for a bill to create a new arboretum in the abandoned field behind your neighborhood. Think of this text as an owner's manual for your life!

CHAPTER OUTLINE

Living Organisms Display Nine Specific Characteristics 4
- Living Things Must Maintain Homeostasis
- Homeostasis Helps an Organism Stay Alive

Human Biology Is Structured and Logical 6
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- Biological Classification Is Logical

Scientists Approach Questions Using the Scientific Method 12
- The Scientific Method Leads to Theories
- Critical Reasoning Is Useful in Human Biology

Scientific Findings Often Lead to Ethical Dilemmas 16

CHAPTER PLANNER

- ❑ Study the picture and read the opening story.
- ❑ Scan the Learning Objectives in each section:
  p. 4 ❑ p. 6 ❑ p. 12 ❑ p. 16 ❑
- ❑ Read the text and study all figures and visuals. Answer any questions.

Analyze key features

- ❑ Health, Wellness, and Disease, p. 5
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- ❑ Stop: Answer the Concept Checks before you go on:
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End of chapter

- ❑ Review the Summary and Key Terms.
- ❑ Answer the Critical and Creative Thinking Questions.
- ❑ Answer What is happening in this picture?
- ❑ Answer the Self-Test Questions.

1.1 Living Organisms Display Nine Specific Characteristics

LEARNING OBJECTIVES

1. **List** the characteristics of life.
2. **Define** homeostasis and relate it to the study of life.
3. **Describe** how homeostasis plays a role in everyday activities.
4. **Contrast** negative and positive feedback systems.

Reflect again on the start of your day. It has just demonstrated many of the characteristics of life (Table 1.1). Several of these characteristics appeared during your first minutes of awakening. Life is defined by the ability to **respond to external stimuli** (remember waking to the alarm?). Objects that are alive can **alter their environment**, as you did by silencing the dreadful noise. You **sensed your environment** when you felt the chill of the morning, then you **adapted to your environment** by covering yourself with clothes to maintain your internal temperature. Living things **require energy**, which plants get by synthesizing compounds using solar power and which animals get by ingesting nutrients, aka breakfast. All of us are proof that living organisms **reproduce**. On the average foggy-headed morning, you undoubtedly failed to notice three other characteristics of life: (1) life is composed of **materials found only in living objects** (your body contains proteins, lipids, carbohydrates, and nucleic acids: DNA and RNA); (2) living organisms maintain a stable internal environment, a property called **homeostasis**; and (3) life exhibits a **high degree of organization**, which extends from microscopic units, called **cells**, in increasingly complex tissues, **organs**, **organ systems**, and individual organisms.

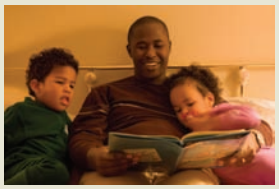
cell The smallest unit of life, contained in a membrane or cell wall.

organ A structure composed of more than one tissue having one or more specific functions.

organ system A group of organs that perform a broad biological function, such as respiration or reproduction.

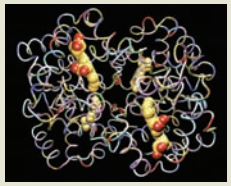
Characteristics of life Table 1.1

Respond to external stimuli



Adapt to the environment

Contain materials found only in living organisms



Alter the environment

Use energy

Maintain a constant internal environment (homeostasis)

Sense the environment

Reproduce

Have a high degree of organization

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Living Things Must Maintain Homeostasis

One key element of life is **homeostasis**, a word that means "staying the same" (*homeo* = unchanging; *stasis* = standing). Humans, along with other organisms, can function properly only if they stay within narrow ranges of temperature and chemistry. Homeostasis allows you to respond to changes in your internal environment by modifying some aspect of your behavior, either consciously or unconsciously. When you are chilled, you consciously look for ways to warm yourself. This morning, you clothed yourself in an attempt to remain warm. If your clothing was not enough, your body would begin to shiver to generate internal heat through chemical reactions. Blood vessels near the surface of your skin would constrict and carry less blood, thereby reducing heat loss through **radiation**. These changes are attempts to maintain homeostasis. (See *Health, Wellness, and Disease: Homeostasis Is a Way of Life!*)

radiation The transfer of heat from a warm body to the surrounding atmosphere.

HEALTH, WELLNESS, AND DISEASE

Homeostasis Is a Way of Life!

THE PLANNER

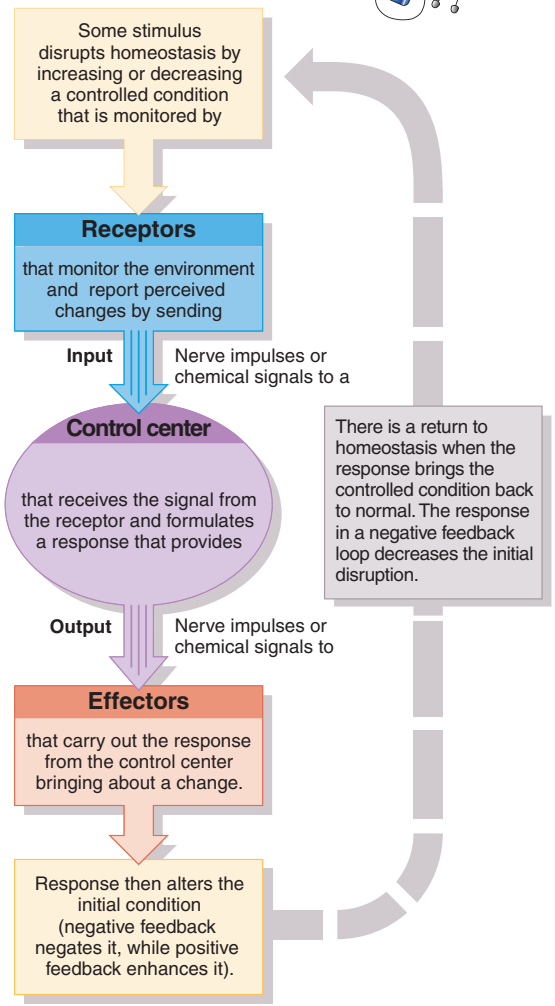
We have all felt tired or "out of sorts" at one time or another. Often, when we experience these episodes, we are functioning under a slight homeostatic imbalance. One accepted definition of disease is, in fact, a homeostatic imbalance with distinct signs and symptoms. Symptoms are the series of complaints we generate when we begin to feel ill. They include headache, nausea, fatigue, and muscle aches. Signs are the changes in bodily function that can be detected by a medical professional. Signs of homeostatic imbalance usually include a full description of the blood chemistry of the individual as well as tests of hormone levels and function.

There are many examples of subtle homeostatic imbalances that, if left unchecked, can lead to serious complications. For example, feeling tired may be due to a lack of oxygen-carrying capacity in the blood, a condition known as anemia. Adding iron to your diet might be all that is needed to reduce chronic fatigue.

Some people require regular food intake to maintain their homeostatic sugar balance. If they wait too long between meals, they may experience nervousness, sweating, trembling, and inability to concentrate, all caused by low blood sugar. Hypoglycemia is the clinical diagnosis for this. The brain responds very strongly to the lack of sugar, and will intensify feelings of hunger so that blood sugar does not reach critical levels. If there is no food immediately available, blood sugar may drop below 50 mg/dl, causing more serious complications such as confusion, drowsiness, coma, or seizure.

Recent studies show that the onset of Alzheimer's disease may be heightened by an imbalance of the copper, iron, and zinc ions in the brain. Treatment for early signs of Alzheimer's disease now includes restoring metal homeostasis. Patients whose metal balance is regulated experience a slower progression of the disease.

Feedback loop • Figure 1.1



Homeostasis Helps an Organism Stay Alive

Homeostasis helps an organism stay alive, often through the use of **feedback systems**, or loops, as shown in Figure 1.1. The most common type of feedback system in the human is **negative feedback**. Negative feedback systems operate to reduce or eliminate the changes detected by the stimulus receptor. Negative feedback prevents you from breathing fast enough to pass out or from drinking so much water that your blood chemistry becomes dangerously unbalanced. Positive feedback systems are rare in the body, and include child birth and blood clotting. The response in a positive feedback system serves to amplify the original stimulus. Feedback is so important that we will return to it when we discuss each organ system.

CONCEPT CHECK

STOP

1. **How** do you display characteristics that indicate you are living?
2. **What** is homeostasis and how does it relate to the study of life?
3. **How** does homeostasis play a role in everyday activities?
4. **What** is the difference between positive and negative feedback?

1.2 Human Biology Is Structured and Logical

LEARNING OBJECTIVES

1. **Explain** how atoms, and therefore the entire field of chemistry, relate to the study of life.
2. **Describe** the organizational pattern of all biology and the logic of taxonomy.
3. **Relate** taxonomy to human biology.

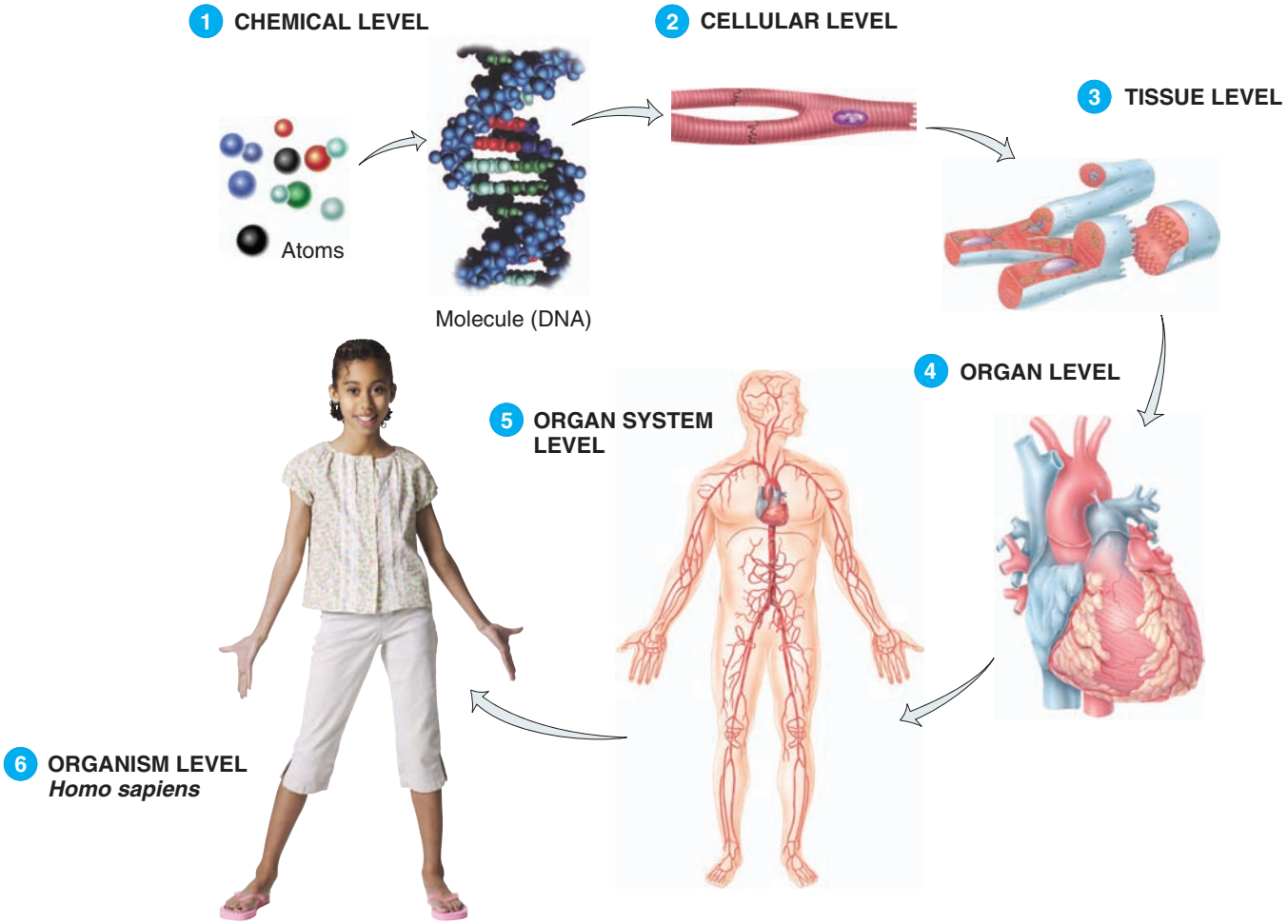
One of the oldest techniques for dealing with our world is to categorize it and divide it into manageable chunks. Imagine trying to understand this paragraph if the sentences were not lumped into words through the use of spaces. Similarly, the natural world seems overwhelming and chaotic until we organize it. Biology is organized in steps, from microscopic to macroscopic: Small units make up larger units, which in turn form still larger units. We see this in both artificial and natural organization in biology. In artificial classification (taxonomy), a system of names is used to identify organisms and show their genetic relationship.

These names identify individual species and also group organisms based on similar characteristics. The categories from species through genus, family, order, class, phylum, and kingdom indicate groups of similar organisms with each category broader than the last.

Organisms Are Structured

Natural organization, in contrast, emerges from the structure of organisms. Both natural and artificial organization help us make sense of the living world. Natural organization appears in the human body as it does in the rest of the living realm. Natural organization is based on a system of increasing complexity. Each level in the hierarchy is composed of groups of simpler units from the previous level, arranged to perform a specific function. The smallest particles that usually matter in biology are atoms, as shown in Figure 1.2. **Atoms** are defined as the smallest unit of an element that has the properties of that element. Atoms combine to form molecules—larger units that can have entirely different properties than the atoms they contain. You already know some of the molecules we will discuss, such as water, glucose, and DNA. Molecules then combine to form **cells**, which are the smallest unit of life. We will take a closer look at the cell in Chapter 4. Groups of similar cells with similar function combine to form **tissues**.

Hierarchy of organization of life • Figure 1.2



Natural organization: from atom to organism

1. Chemical level: the chemical "components" that are arranged into cells (atoms to molecules)
2. Cellular level: the smallest unit of life; a component bounded by a membrane or cell wall; in multicellular organisms, cells are usually specialized to perform specific functions (for example, muscle cell)
3. Tissue level: an assemblage of similar cells (for example, muscle)
4. Organ level: an assemblage of tissues that often have several functions (example, heart)
5. Organ system level: the group of organs that carries out a more generalized set of functions (example, cardiovascular system)
6. Organism level: *Homo sapiens*

Hierarchy of life beyond the individual • Figure 1.3

a. Individual or species

b. Human Population
Populations are comprised of all individuals of a given species in a specified area.

c. Biological Community
Human populations live in concert with populations of other organisms, interacting in a larger concept called the community.

d. Ecosystem
Communities are united in geographic areas, interacting with one another and the physical environment in a biome. The Earth has many biomes, such as the open ocean, high sierra, desert, and tropical rain forest.

e. Biosphere
Finally, all Earth's biomes comprise the biosphere.

The human body has four major tissue types: muscular, nervous, epithelial, and connective. Tissues working together form organs, such as the kidney, stomach, liver, and heart. **Organs** with the same general function combine to form **organ systems**. For example, the respiratory system includes organs that work together to exchange gas between cells and the atmosphere; organs in the skeletal system support the body and protect the soft internal organs. A suite of organ systems combine to form the human **organism**. Notice that each layer of complexity involves a group of related units from the preceding layer. This type of hierarchy is found throughout biology and the natural world.

Taking a global view of the organization found in the natural world, we see that the concept of hierarchy does not stop at the individual. The individual human organism lives in groups of humans called **populations**, as shown in **Figure 1.3b**.

population All representatives of a specific organism found in a defined area.

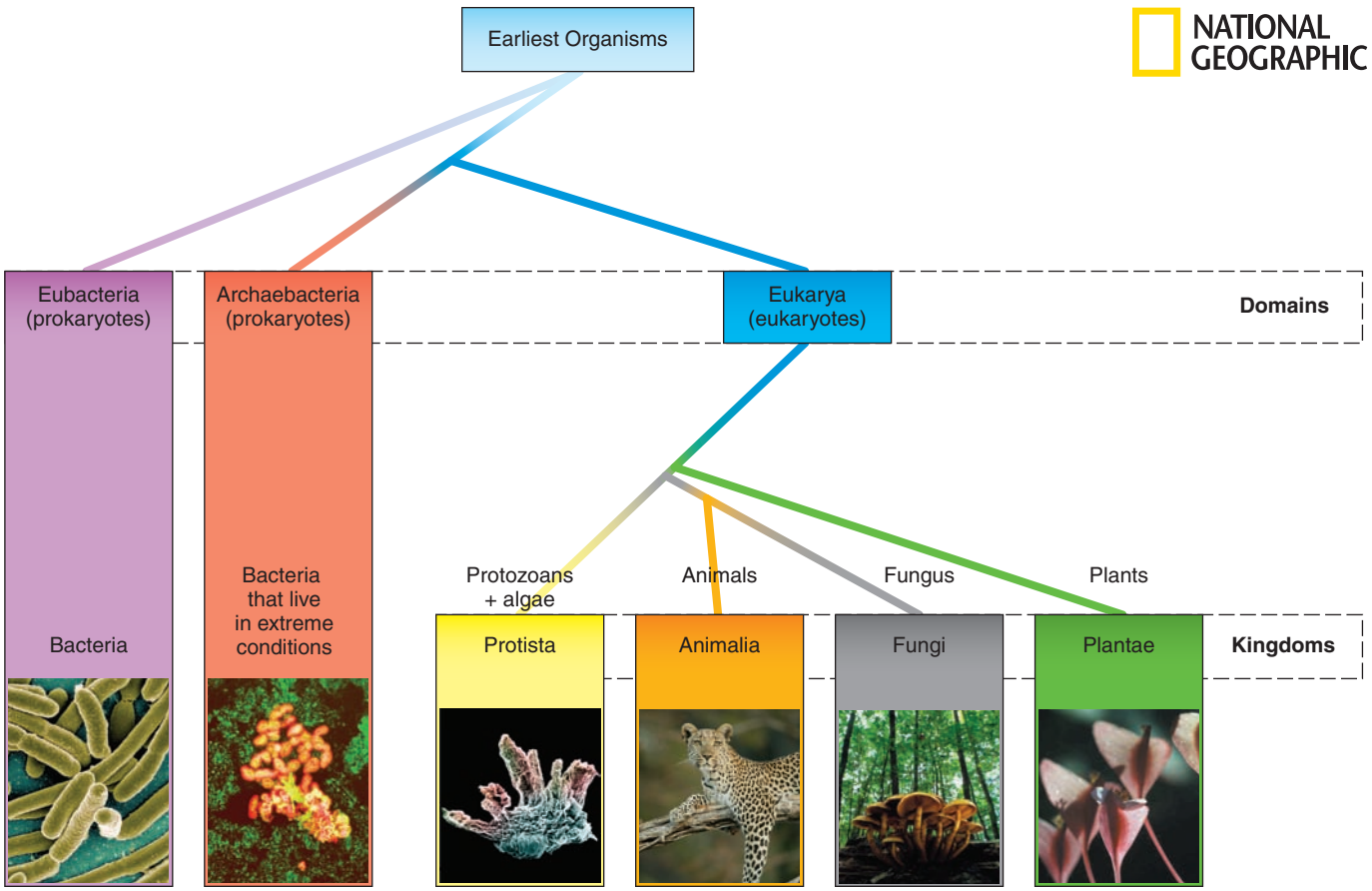
Biological Classification Is Logical

Biology tries to make sense of myriad observations of the biosphere by classifying organisms into groups with similar characteristics. The branch of science dealing with this organizational scheme is called **taxonomy**. One of the best-accepted taxonomic schemes starts from the most inclusive, with three domains and six **kingdoms** (see **Figure 1.4**). The domain Eukarya includes organisms whose cells contain nuclei and internal membranes. The four kingdoms in Eukarya are **Animalia** (the animals), **Plantae** (the plants), **Fungi** (the fungi), and **Protista** (the one-celled organisms that possess nuclei). The two remaining kingdoms are the prokaryotic **Eubacteria** and **Archaebacteria** (the bacteria and other one-celled organisms without nuclei). It is worth noting that unlike bacteria, viruses are not classified as living—see *I Wonder… Are Viruses Considered Living Organisms?* on the next page.

taxonomy The study of classification, based on structural similarities and common ancestry.

kingdom A high-level taxonomic classification.

Domains and kingdoms • Figure 1.4



Human taxonomy • Figure 1.5

Meet your human taxonomy:

KINGDOM
Animalia
(all multicellular organisms that ingest nutrients rather than synthesize them)

PHYLUM
Vertebrata
(all animals with a vertebral column or **dorsal hollow notocord**—a structure along the top of animals—protecting their central nervous system)

CLASS
Mammalia
(all vertebrates with placental development, mammary glands, hair or fur, and a tail located behind the anus)

ORDER
Primates
(mammals adapted to life in trees, with opposable thumbs)

I WONDER...

THE PLANNER

Are Viruses Considered Living Organisms?

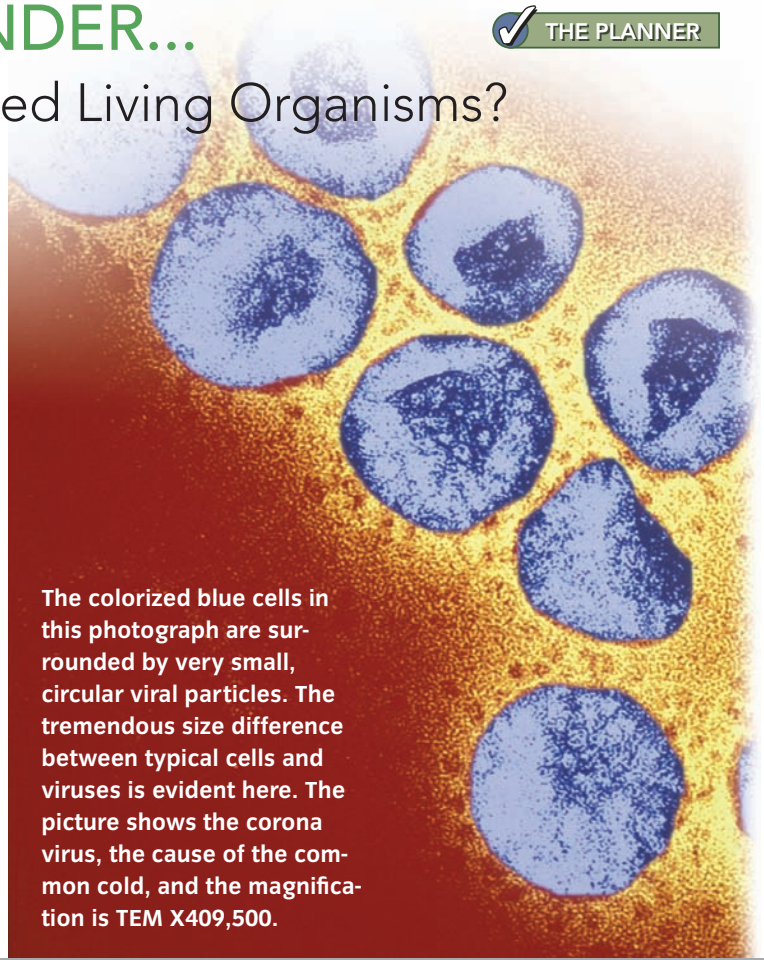
Viruses are among the smallest agents that can cause disease, and they cause some of the worst diseases around. Scientists think that smallpox, caused by the *variola* virus, killed more people in the past few centuries than all wars combined. HIV, the human immunodeficiency virus, causes AIDS, whose death toll continues to mount year after year.

Because viruses are less than 1 micron (millionth of a meter) across, they were not discovered until early in the nineteenth century. Viruses are much smaller than bacteria, which are single-celled organisms that are truly alive.

We know viruses can kill. To determine whether they are alive, we refer to the required characteristics of life, and we observe that viruses lack many of them, such as:

- cells (viruses are basically a protein coat surrounding a few genes, made of either DNA or RNA);
- the ability to reproduce;
- the ability to metabolize or respire; and
- a mechanism to store or process energy.

Viruses can reproduce but only if they can slip inside a host cell and seize control of its internal machinery. Viruses are more complex than prions, the distorted proteins that cause bovine spongiform encephalopathy—mad cow disease. However, viruses are far simpler than even a bacterial cell. So although viruses are not alive, they are the ultimate parasite.



The colorized blue cells in this photograph are surrounded by very small, circular viral particles. The tremendous size difference between typical cells and viruses is evident here. The picture shows the corona virus, the cause of the common cold, and the magnification is TEM X409,500.

FAMILY
Hominidae
(primates that move primarily with bipedal—two-footed—locomotion)

GENUS
Homo
(hominids with large brain cases, or skulls)

SPECIES
H. sapiens
(the largest brain case of the genus *Homo*, giving us the capacity for complex speech; "*sapiens*" loosely translates as "knowing")
We are the only living organisms in our species, with a unique set of combined characteristics from our family (bipedal), order (opposable thumbs), and genus (large brain case).

Each kingdom is further classified, based on similar characteristics, into divisions that get ever more narrow: **phylum**, **class**, **order**, **family**, **genus**, and **species**. Each category defines the organisms more tightly, resulting in a hierarchy of similarity. The final category, species, implies reproductive isolation, meaning (with very few exceptions) that members of a particular species can produce **viable** and fertile offspring only if they breed with each other.

species A precise taxonomic classification, consisting of organisms that can breed and produce offspring capable of breeding.

viable Capable of remaining alive.

Taxonomists capitalize the first letter of all classification terms except species (*Homo sapiens*). The species name is always preceded by the entire genus name, unless you have just mentioned the genus; then you can abbreviate it: "In regard to *Homo sapiens*, we must note that *H. sapiens* . . ." Genus and species names are either underlined or written in italics, as shown in **Figure 1.5**.

Each successive category refines the characteristics of "human" to the point where only humans are classified in the final category, *Homo sapiens*. Despite the amazingly complex and pervasive cultural differences that exist between populations of humans, we are all members of the same species.

CONCEPT CHECK

1. **How** do atoms relate to the study of life?
2. **What** is the broad organizational pattern of biology and how does taxonomy work?
3. **What** can you discover about an organism by comparing its full taxonomic classification to that of a human?

1.3 Scientists Approach Questions Using the Scientific Method

LEARNING OBJECTIVES

1. **List** the steps in the scientific method in order.
2. **Define** hypothesis and theory.

Science is a field with specific goals and rules. The overall goals are to provide sound theories regarding the phenomena we observe, using rules embodied by the **scientific method**. When a question arises about the natural world, the scientific method provides the accepted, logical path to the answer, as shown in **Figure 1.6**.

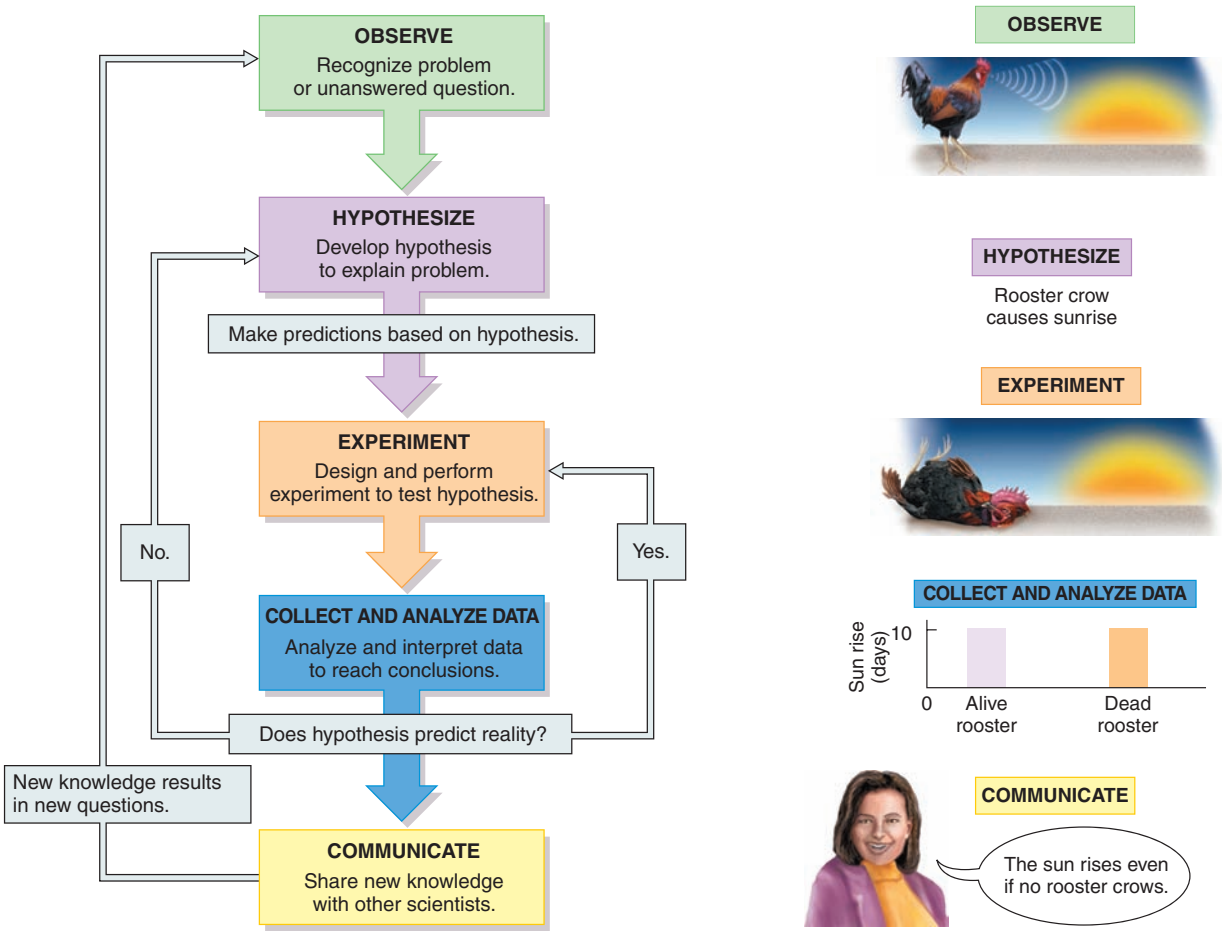
A scientific experiment is an exercise in logic: Our goal is to prove our hypothesis wrong. For example, our hypothesis is that the rooster's crow causes the sun to rise within the next 20 minutes. How could we test this

PROCESS DIAGRAM

THE PLANNER

The scientific method • Figure 1.6

The scientific method is rooted in logic. If we can show that our hypothesis does not apply to even one situation, then our hypothesis is wrong. After we analyze the data and draw conclusions from them, we may have to junk our hypothesis, or conclude that it applies to a more limited range of circumstances.



hypothesis? Could we force the rooster to crow at midnight, and wait 20 minutes for a glow on the eastern horizon? Could we prevent the rooster from crowing in the morning? In either case, if the sun rose as usual, our hypothesis would be disproved, and we would need to find a better hypothesis.

This silly example shows how scientists may manipulate factors that (according to the hypothesis) seem related to the observation, all in an attempt to disprove the hypothesis. We develop a hypothesis using **inductive reasoning**—creating a general statement from our observations. We design the experiment, however, with **deductive reasoning**, moving from the general hypothesis to a specific situation. An "if, then" statement is an ideal basis for a scientific experiment: "If situation A (rooster crows) occurs, then result B (sunrise) will follow." In our experiment, we changed situation A and monitored any changes in result B.

When designing and running the experiment, we must control all potential **variables**. Otherwise, we cannot draw any valid conclusions. In the rooster example, it would be a good idea to muzzle all nearby roosters. Otherwise, how would we know whether our bird or a bird in the next chicken coop had caused the sunrise? Similarly, in testing new medicines, scientists use a "double-blind" experiment: Nobody knows whether each research participant is getting real medicine or a fake, called a "placebo." This prevents expectations that the drug will work from actually causing a change in the participant's health. The "placebo effect" can be powerful, but the goal is to test the drug, not the research participant's expectations.

variable A factor that can be changed in an experiment to test whether and how it affects the outcome.

statistical significance An experimental result that would occur by chance in less than 1 experiment in 20; the accepted level in modern science.

Finally, our hypothesis must be testable and falsifiable. If we cannot think of a situation where we could disprove it, there is no experiment to devise. Learning to assess situations with the scientific method takes some practice, but it's a skill that can be useful throughout life.

Let's take an example from human biology to show the process of testing a hypothesis. Have you seen those hand lotions that claim to be "skin firming"? Sounds great, but how would we test this claim? Under the scientific method, we consider the marketing claim to be the observation, so we must develop a testable hypothesis from the observation: "Using this hand cream for one month will cause measurable tightening of the skin on the back of the hand." Now we restate the hypothesis as an "if, then" statement: "If the cream does firm the skin, then using the cream on the back of the hand for one month will reduce the skin-fold measurement." This is a testable statement that lends itself to controlled experimentation. First, we will assess each person's skin tautness by measuring the skin fold that can be pulled up on the back of the hand. Then we will randomly divide the participants into two groups: a control group and an experimental group. We will treat each group in an identical manner, except that the control group will use Brand X hand cream without the firming agent and the experimental group will get Brand X with the firming agent. After using the cream for one month, we will repeat the skin-fold measurements and analyze our data, looking for changes in skin tautness between the two groups as evidence for either accepting or refuting the hypothesis. If the experimental group displays a change in tautness that would occur by chance in less than 1 experiment in 20, the change is said to have **statistical significance**, and the hypothesis is supported: The cream does tighten the skin.

It is important to note that any conclusions drawn from a scientific experiment must be supported by the data. If the results of your experiment could have happened by chance, you cannot say that the results were due to the experimental design. In that case, a new experiment must be designed and run.

The Scientific Method Leads to Theories

Because biologists cannot always control all factors, or variables, that might affect the outcome, they often use observation as a form of experimentation. If you were interested in the effects of mercury on the human brain, it would not be ethical to dose people with mercury, but you could perform an observational study. You could measure blood levels of mercury, or you could ask your research participants about past diet (food, especially fish, is the major source of mercury exposure). Then you would use statistical tests to look for a relationship between mercury exposure and intelligence. Finally, you could try to confirm or refute your results with controlled experiments in

lab animals. Does mercury make rats faster or slower at negotiating a maze (a standard test for rat intelligence)? Observational studies are also a mainstay of field biology.

Observation, experimentation, and analysis are the basis for scientific reasoning. Once a group of related hypotheses have survived rigorous testing without being disproved, they are accepted as a **theory**. Theories are not facts but rather extremely well-supported explanations of the natural world that nobody has disproved. To a scientist, a theory is much more than a hypothesis or a belief—it's our best effort to date to explain nature. Many fields of science may be involved in supporting a theory. The theory of evolution through natural selection, for example, is supported by taxonomists, geologists, paleontologists, geneticists, and even embryologists. Many scientists have tried, but none has refuted the basic hypothesis first described by Charles Darwin in 1859. We will discuss another key theory, the cell theory, in Chapter 4.

theory A general uniting principle of science, upheld by observation and many experiments.

Science is not a perfect, set-in-stone answer to questions about the natural world but rather a dynamic, ever-changing collection of ideas. New information can change or destroy accepted explanations for the natural world. For example, doctors once blamed contagious disease on ill humors, miasmas, and evil spirits. Through the work of nineteenth-century biologist Louis Pasteur, it became clear that many diseases were caused by microscopic organisms. In his breakthrough experiment, Pasteur sterilized some grape juice and showed that it did not ferment into wine. Then he added yeast, and the juice fermented. When Pasteur showed through experiment that invisible organisms can also cause disease, he helped establish the germ theory of disease. Although it's called a theory, the germ theory is the universally accepted scientific explanation for infectious disease. More recently, the accepted role of the cell nucleus has come into question. Based on experiments, biologists used to consider the nucleus the cell's control center, but new evidence suggests it actually functions more like a library for genetic data. The actual control of gene expression and cellular activity seems to reside outside the nucleus, in specific RNA molecules. The theory of nuclear control in the cell is under serious scrutiny, and further experiments could alter it.

Scientific studies are part of the daily news. As technology advances, humans confront scientific hypotheses and experimental results almost every day. We see advertisements for new drugs. We hear that fossil fuels are warming the globe. We see countless new technologies in the field of consumer electronics. In medicine, we hear about a steady stream of new surgeries and wonder drugs. We are told of many ways in which humans are causing the loss of rain forests, coral reefs, natural forests, and plains, as well as the animals that live there. We worry about the causes of animal extinction (see *Ethics and Issues: Why Should Endangered Species Matter to Me?* for a discussion of this). About the only way to wade through the morass of information in the media is to understand and use the scientific process. Responsible citizens living in technological cultures sometimes must make decisions about contested scientific issues they read about in the media. Some reports have linked the radiation from cell phones to brain tumors, but other reports find no connection. A few concerned citizens have demanded that manufacturers produce "safer" cell phones, with lower radiation emissions. Can you think of an experiment that would resolve this issue, at least in principle? As you read about the scientific studies on this issue, ask yourself: What types of controlled and observational experiments underlie the claims about cell phones and cancer? Are the experiments convincing?

Critical Reasoning Is Useful in Human Biology

The ability to question and criticize—for example, our constantly changing understanding of obesity or the dangers posed by food additives or environmental chemicals—is useful in many aspects of human biology. Critically analyze the data, experiments, and claims before you accept what you read. There are plenty of opinions out there; don't accept any until you consider the evidence and reach an informed decision. Form your own opinion based on what you understand to be true.

In other words, become a critical reasoner! Critical reasoners are skeptical, logical, and open to new information, enjoying the way it changes their previous assumptions and ideas. Critical reasoners question assumptions and stated facts, using logic to arrive at their own conclusions. They find good analogies for information that they find to be true, often helping others make sense of the new information. Taking on the role of a critical thinker means recognizing that you don't have to settle for a story or a very

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ETHICS AND ISSUES

THE PLANNER

Why Should Endangered Species Matter to Me?

About 20 years ago, biologists began to realize that they would start to run out of things to study due to the accelerating wave of extinctions shaking the planet. Extinctions occur for many reasons; overhunting, destruction of habitat by fire, construction, or ecological change, and invasion of exotic species can all play a role.

What's the big deal? Some extinction is natural, after all. Why is it important to prevent endangered species from going extinct? The answers range from scientific to economic to spiritual:

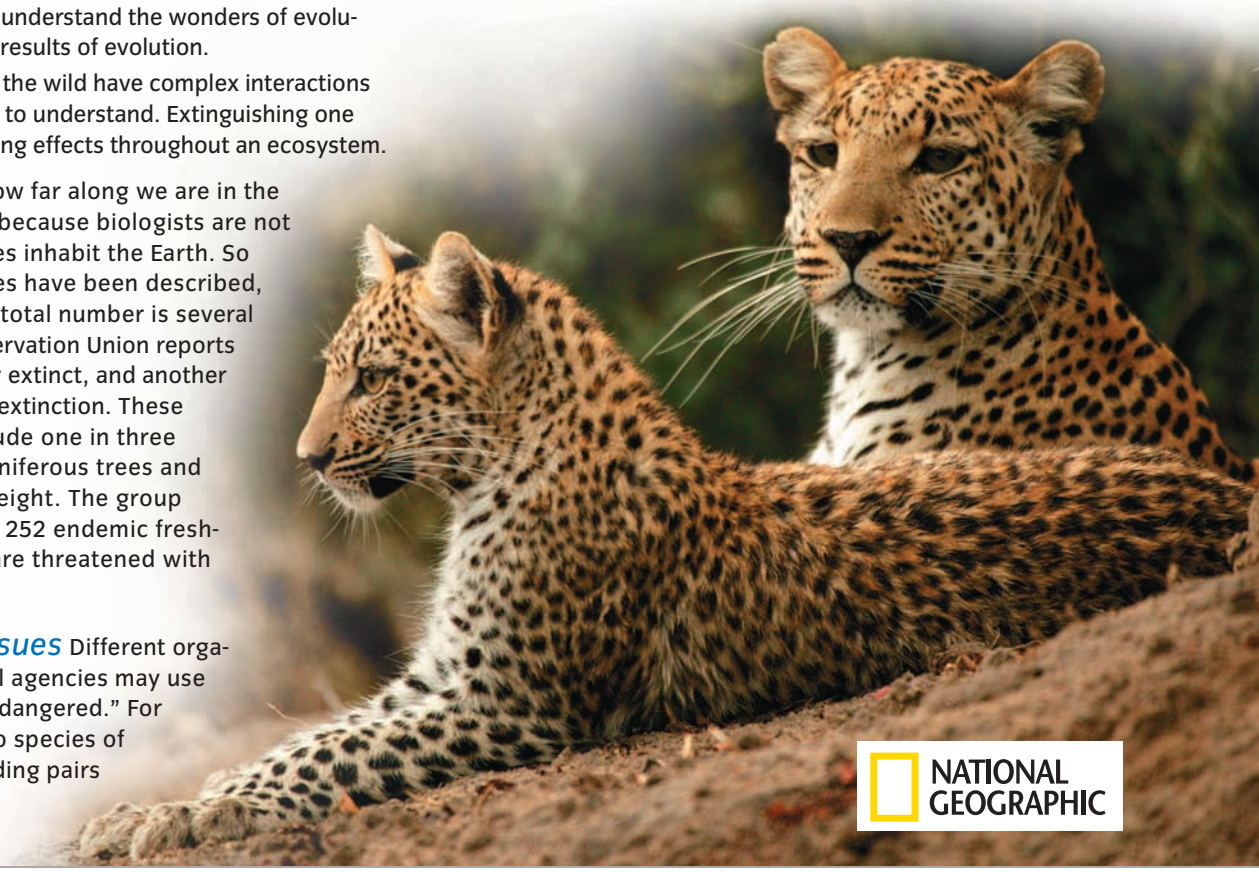
- Organisms can be useful. A species of plant called the rosy periwinkle was the source of a key drug that defeats one type of leukemia. Scientists are actively looking in many unusual ecosystems for useful chemicals that organisms have evolved for specific reasons. Many antibiotics, for example, were derived from fungi that evolved these compounds for protection against bacteria.
- Life is unique. As far as we know, this is the only planet with life. If we respect life, we should respect its myriad forms as well: the whales, swans, lobsters, and even the endangered fish and mussels in our streams.
- Life has scientific value. To understand the wonders of evolution, we need to study the results of evolution.
- Life is a web. Organisms in the wild have complex interactions that we are only beginning to understand. Extinguishing one organism can have cascading effects throughout an ecosystem.

It's hard to know exactly how far along we are in the current wave of extinction because biologists are not even sure how many species inhabit the Earth. So far, about 1.9 million species have been described, but it is estimated that the total number is several times that. The World Conservation Union reports that 748 species are already extinct, and another 16,119 are threatened with extinction. These threatened organisms include one in three amphibians, one in four coniferous trees and mammals, and one bird in eight. The group also notes that "56% of the 252 endemic freshwater Mediterranean fish are threatened with extinction."

Critical Reasoning Issues Different organizations and governmental agencies may use different data to define "endangered." For some, the term may refer to species of which fewer than 500 breeding pairs are known in a certain country; for others, the data set may encompass the whole continent. Knowing the expertise and motives of an organization or agency may be crucial to understanding how it uses and presents data. However, regardless of technical definitions of "endangered," some of the organisms that are currently becoming extinct are ones we have not even yet identified, let alone studied. Their beauty and utility will go completely unrecognized as they fade from existence. Although evolution may eventually restore biodiversity to its current levels, that will take millions of years. Thus, in biodiversity, as in so many things, a gram of prevention is worth a kilo of cure!

Think Critically

1. What examples can you find of a governmental agency or organization that does not specify its definition of "endangered" and "threatened with extinction"?
2. What are some other reasons to value biodiversity besides the ones mentioned?



small sample size when looking for facts about an issue. You should ask yourself, "Were there enough trials done to see that the results were repeated consistently?" Also, critical reasoners know that there are limits to certainty but do not allow this knowledge to prevent them from seeking as full an understanding of an issue as possible.

People have the ability not only to communicate in complex ways but also to record the past. We can consult studies, relate current affairs to similar historical events, and use statistics to support our reasoning. In so doing, we understand that the past proves the law of unintended consequences—that actions often have unexpected effects. For example, using naturally cool stream water as an industrial plant coolant saves money and seems to be a good use of the available resources. However, the practice dramatically increases the temperature of these streams below the plant. The temperature increase, in turn, changes the population of organisms that are able to survive there and often alters the productivity of the entire watershed below the plant.

Critical reasoning is not the kind of thinking illustrated by the fact that 87% of people rate themselves above average in intelligence. It is also not illustrated by the notion that because a woman was cured of her epilepsy after being bitten by a rattlesnake, the venom caused the cure. Rather, critical reasoning is the best way to understand complex interactions such as those that take place within the human body and between the body and its external environment. Studying human biology is the perfect way to practice your critical reasoning skills, as you will be investigating the most complex system we know—ourselves and our relationship to our environment.

CONCEPT CHECK

1. **What** are the steps of the scientific method?
2. **What** is the difference between a hypothesis and theory?

1.4 Scientific Findings Often Lead to Ethical Dilemmas

LEARNING OBJECTIVES

1. **Define** altruistic behavior.
2. **Briefly describe** why a basic knowledge of science is essential to being a productive citizen.

Humans have evolved as social animals, following the rules and expectations that make life possible in groups. This cultural structure that overlies the biological structure of human life certainly adds interest to our study of human biology. Culture generally requires that people accept responsibility for other individuals within the population, rather than merely surviving and protecting their young. Although **altruistic** behavior does appear among some primates, it helps distinguish humans from other life-forms and creates one basis for the governments and laws people have established.

altruistic Putting the needs of others ahead of, or equal to, personal needs.

ethical decision A decision based on the principles of right and wrong, rather than on financial, personal, or political gain.

When individuals must make judgments and act for the good of the group rather than the individual, they must make **ethical decisions**, and ethical decisions should be informed decisions. Where does that information come from? Scientific research provides our basic understanding of the natural world. Although humans can and do add their interpretations and values to the results of science, science itself is judgment free. Scientific results are neither good nor bad; they are just the best current idea of how the material world operates. The discovery by Pasteur and his peers that germs cause many diseases was neither good nor bad—it was just true. The ability to analyze scientific issues is essential in an informed society and turns out to be more important as scientifically based issues become even more common and complex. Science seeks to explain the natural world, but

Nuclear power • Figure 1.7

Nuclear power poses an interesting mix of scientific and political issues. Atomic fission can provide a large amount of electricity, and it does not create greenhouse gases, which warm the globe and threaten harm to the biosphere. However, radioactive waste is dangerous, and nuclear plants can melt down and spew vast amounts of radiation, as one did at Chernobyl in the Soviet Union in 1986. The decision to use nuclear power is a political decision, not a scientific one, so it is imperative that each member of society understands the scientific data on nuclear reactors, as well as the social ramifications of that information.

Nuclear power has its pluses and minuses. To take a position, you should know about global warming, radioactive waste, and the costs and benefits of other technologies for making electricity—all scientific issues.

Hiding from the truth and not engaging in personal critical thought • Figure 1.8

Is this any way to run an informed citizenry?

the uses of science, both beneficial and harmful, grow from human choices. Sometimes people choose to use scientific discoveries to improve the environment and the human condition, and sometimes they use them to carry out seemingly evil designs. One example of this can be seen in **Figure 1.7**. Another example of this dual edge is the understanding that germs cause disease. Pasteur's germ theory of disease can be used to help cure disease—or to invent biological warfare.

Many ethically charged scientific issues, such as stem cell research, environmental conservation, or genetically modified food, have both personal and political ramifications. Each of these requires an understanding of the science and the societal issues. An informed voting public requires that each individual draw logical and defensible conclusions from scientific information. The alternative is **Figure 1.8**.

CONCEPT CHECK

1. **What** is altruistic behavior?
2. **Why** is it important to understand scientific information?

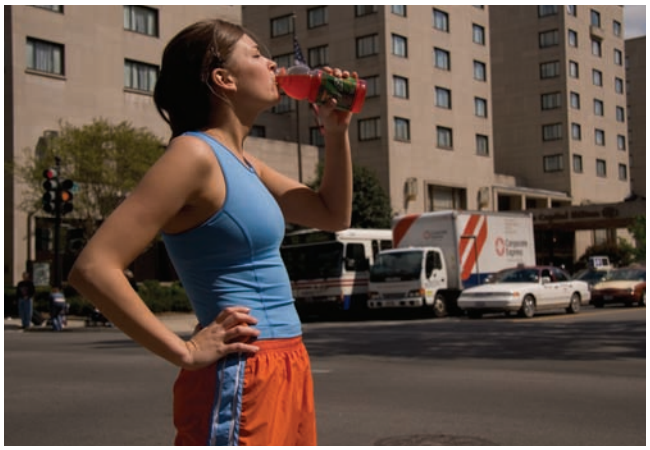
Summary

THE PLANNER

1 Living Organisms Display Nine Specific Characteristics 4

- Cell biology is the study of life. One characteristic of life is organization. Living things are organized from microscopic to macroscopic. All life is also composed of cells and is responsive to the environment. Life adapts, uses energy, and reproduces.
- Living organisms are composed of carbohydrates, lipids, proteins, and nucleic acids. In order to maintain life, these organisms must maintain a relatively constant internal environment, called "homeostasis," as shown here. This is accomplished through a feedback system, including a receptor, a control center, and an effector. The usual feedback system in the body is a negative feedback system.

Table 1.1



2 Human Biology Is Structured and Logical 6

- The natural organization of life on Earth is based on a system of increasing complexity, as shown in the figure. The base of this hierarchy is atoms, meaning that the basis of biology is actually chemistry. Atoms combine to form molecules. Molecules join together to form cells. Similar cells form tissues; tissues with a common function form **organs**; organs with similar functions form **organ systems**; and a group of organ systems all functioning together form an **organism**.

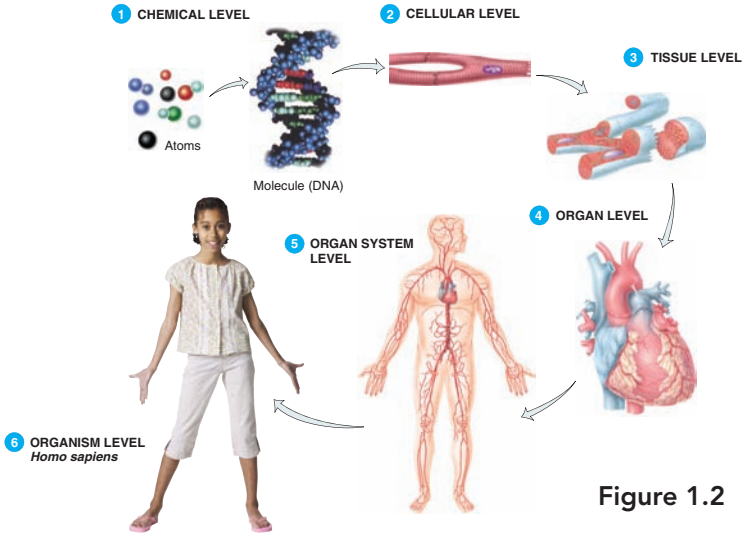


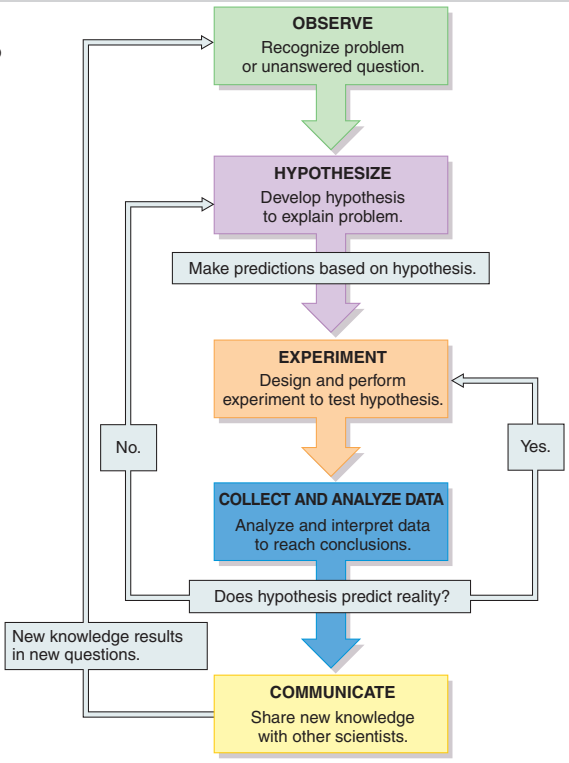
Figure 1.2

- **Taxonomy** is the study of classification. Organisms are classified based on shared characteristics. Each successive level gets more restrictive, until only one interbreeding species is described.

3 Scientists Approach Questions Using the Scientific Method 12

- Science is more a way of thinking than a body of knowledge.
- As you can see here, the steps of the scientific method include:
  - Observation: witnessing an unusual or unexpected phenomenon
  - Hypothesis: formulating an educated guess as to why the phenomenon occurs
  - Experiment: designing and running a controlled experiment to test the validity of the hypothesis
  - Collecting results and analysis: recording the results of the experimental procedure and determining the meaning of the results obtained from the experiment
  - Communicating the findings: preparing a paper, presenting a poster, or speaking about the results of the experiment

Figure 1.6



4 Scientific Findings Often Lead to Ethical Dilemmas 16

- Science in and of itself is neither inherently good nor bad. It is in the use of scientific principles that value judgments are made, as shown here. Science can be used for either the betterment of society or its destruction.

Figure 1.7

- Individuals who understand the ramifications of a science are the ones who should decide about its use. In democratic nations, however, these ethical decisions are placed in the hands of the voting populace. In order to make the right choices, we must all understand at least a little bit about the functioning of the biological world in which we live. We must become critical reasoners.

Key Terms

- altruistic 16
- cell 4
- ethical decision 16
- kingdom 9
- organ 4
- organ system 4
- population 9
- radiation 5
- species 11
- statistical significance 13
- taxonomy 9
- theory 14
- variable 13
- viable 11

Critical and Creative Thinking Questions

1. Gerald proudly displays his pet rock, complete with its cardboard cage, in his bedroom. His sister, Marianne, has a Chia Pet in her bedroom. Her Chia Pet is a planter shaped like a puppy, with sprouts simulating fur growing on the puppy planter's back and head. Using the characteristics of life listed in the beginning of this chapter, argue that either pet is alive. Explain why the other pet is not alive.

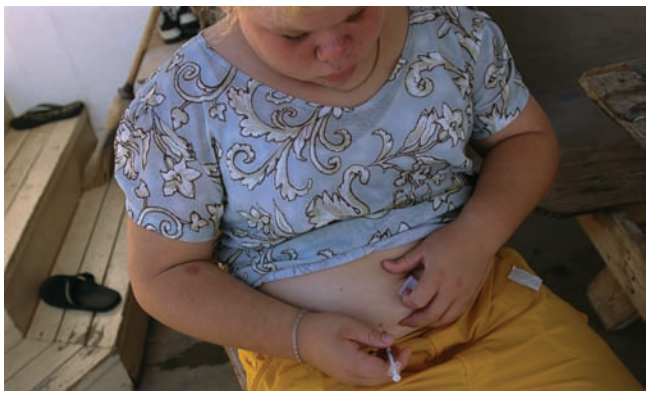
2. When considering the increasing complexity of atoms, molecules, cells, and tissues, you may notice that each step has characteristics that were absent in the previous level. These characteristics, called emergent properties, demonstrate that the whole organism is more than the sum of its individual parts. Consider the heart, an organ with a variety of tissues. In what way is the heart more than the sum of the tissues it comprises?

3. CLINICAL CLICK QUESTION
Jan often feels shaky, irritated, and unfocused immediately before her next meal. She finds that she is unbearably hungry at times and yet is still losing weight. Most alarmingly, she has recently suffered from bouts of blurry vision. Her doctor recognizes that these symptoms are due to a homeostatic imbalance. Jan has found that she can control her odd reaction to meals if she continually eats small portions of food throughout the day. When she explains this to her doctor, she is asked to submit to a glucose tolerance test designed to analyze her body's ability to tolerate large amounts of sugar entering the bloodstream at once.

Can you predict what homeostatic imbalance Jan suffers from?

Insulin is a compound produced by the body that permits sugar from the bloodstream to enter the cells of the body, reducing the level of sugar in the blood. Normally, as blood sugar rises insulin production increases. What type feedback system is this?

How might Jan's doctor begin to treat Jan's inability to regulate her blood sugar? Visit the Web site http://www.medicinenet.com/diabetes_melitus/article.htm to verify your conclusions, and create a treatment regime for Jan.



4. Taxonomy places organisms in smaller and smaller categories, each with more restrictive criteria, until a particular organism is defined so tightly that no other can share that classification. Look at the classification for humans. Where would an organism diverge from the human lineage if it had not developed an arboreal (tree-dwelling) existence? Where on the taxonomic tree would a bipedal placental mammal with a tiny brain case diverge?
5. Dr. Pamela Sullivan claims that her new toothpaste whitens teeth five times faster than other toothpastes. How would you design a controlled experiment to test Dr. Sullivan's hypothesis?

What is happening in this picture?

SCIENTISTS IN THE FIELD COLLECTING EXPERIMENTAL DATA

Field ecologists, like many other biologists, must rely on observational studies rather than controlled experiments. These scientists are taking samples of the arctic ice using a coring device. They remove long cylinders of ice, then observe the changes in the chemistry of the ice with depth.

Think Critically

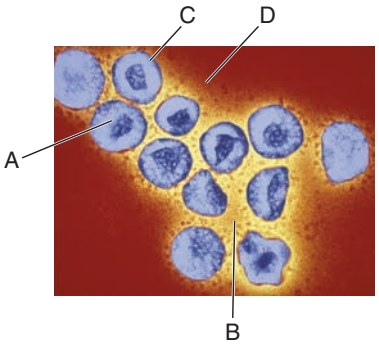
1. How do you suppose these changes are "observed"?
2. What specific chemical changes would scientists expect to see between ice that formed in the 1200s and ice that formed in the early 1900s?

Self-Test

1. Which of the following is not a characteristic of life?
   a. responds to external stimuli
   b. has a low degree of organization
   c. is composed of proteins, lipids, and carbohydrates
   d. maintains a stable internal environment

2. Which of the following items represents the smallest unit of life?
   a. organism
   b. organ
   c. tissue
   d. cell

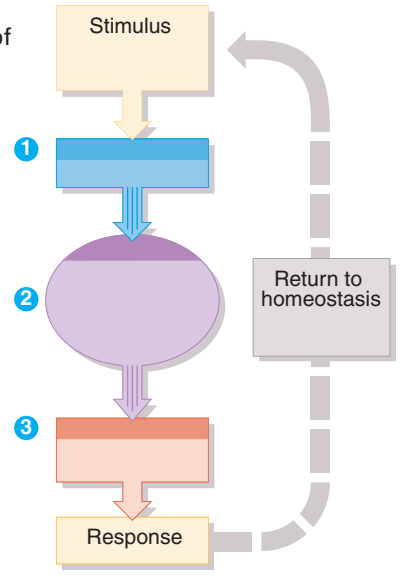
3. On the figure below, identify the nonliving portion.
   a. A
   b. B
   c. C
   d. B and D



4. Using the same figure from question 3, what is structure C?
   a. a viral particle
   b. tissue
   c. a cell
   d. an organ

5. Homeostasis is maintained most often by ____.
   a. positive feedback systems
   b. negative feedback systems
   c. warm-blooded animals
   d. viruses
   e. radiation

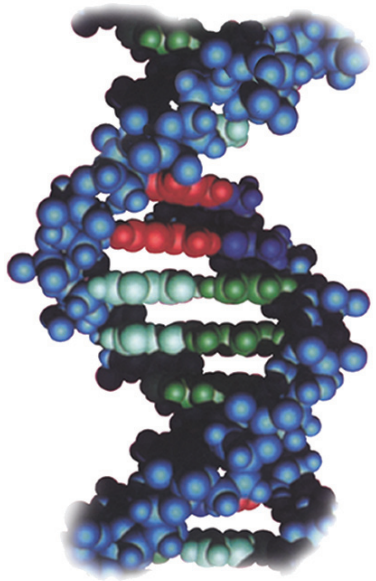
6. Identify the components of a typical feedback system by writing the following terms on the diagram:
   a. receptor
   b. effector
   c. control center



7. Which of the components of a typical feedback system is responsible for altering behavior to reduce the original stimulus?
   a. receptor
   b. effector
   c. control center

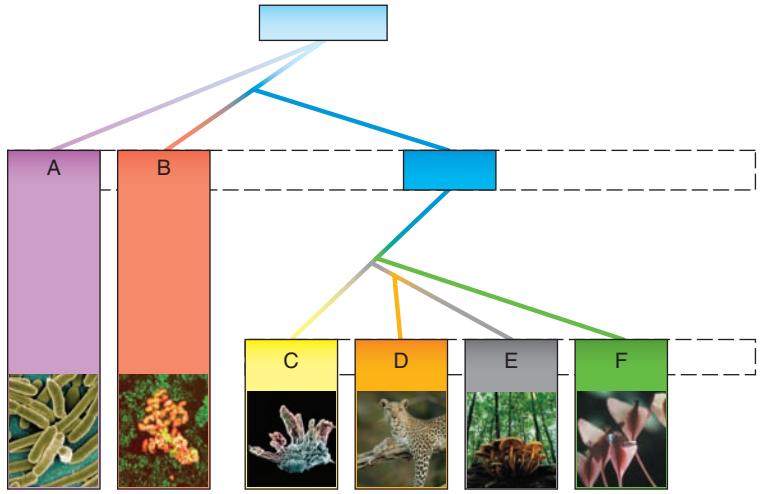
8. The organism in the photo is demonstrating what type of homeostatic mechanism?
   a. negative feedback
   b. positive feedback
   c. ion control
   d. water balance

9. What level of organization is indicated by the figure below?
   a. cellular level
   b. organ level
   c. organ system level
   d. chemical level



10. Of the levels listed, which is the most complicated?
   a. organism level
   b. cellular level
   c. organ level
   d. organ system level
   e. chemical level
   f. tissue level

11. In which kingdom are humans found?
   a. A
   b. B
   c. C
   d. D
   e. E
   f. F



12. Which of the following taxonomic levels includes organisms that can interbreed and produce viable offspring?
   a. genus
   b. species
   c. family
   d. phylum

13. Anyone can employ the scientific method to answer questions they have about the world around them.
   a. true
   b. false

14. In the figure below, what step of the scientific method is most likely being practiced?
   a. hypothesizing
   b. observing
   c. communicating
   d. experimenting

15. If a scientific discovery has both personal and political ramifications, it would be best to _____.
   a. rely on the media to inform you of the best use of the discovery
   b. read one small article in your local paper to stay informed
   c. read and evaluate every article that you can find on the subject
   d. ask your neighbors what they think, and go along with their opinion

THE PLANNER

Review your Chapter Planner on the chapter opener and check off your completed work.

2 Where Do We Come from and Where Do We Fit?

"But Miss, why is human biology taught in the Zoology department? Isn't zoology the study of ANIMALS?" The student asking this question stood in the lecture hall, sporting an armload of books and a quizzical expression. Perhaps it had never occurred to her to think about humans in this light. We are, in fact, animals. We are multicellular; we cannot manufacture our own food; we undergo an embryonic developmental stage; and we are mobile. In addition, we require food, shelter, and the company of others. The environment in which we live shapes our lives, and we in turn have shaped that environment.

When we really look at ourselves, we find very little separating us from the chimpanzee. Our DNA, the hereditary molecule, is at least 98% identical to that of the chimp. Both chimpanzees and humans form cooperative groups for hunting and socializing. Both use tools. Chimps rear their young for at least five years, and family groups form bonds that remain for lifetimes. Even more basic, humans and other animals respond to changes in their environment by short- and long-term adaptations. These adaptations can be changes in behavior, in food choices, or even in body form over long periods of time.

We are biological beings, and as such we are subject to the same laws, theories, and ideas as the rest of the biological world. So, while we like to think of ourselves as above the life struggles of, say, earthworms, it is really not the case.

WILEY PLUS Video

CHAPTER OUTLINE

What Are the Origins of Modern Humans? 24

- The Human Ancestors Are Dead Twigs on the Family Tree
- *Homo Sapiens* Appears and Starts to Change Everything

What Does the Human Body Have in Common with the World Around It? 31

- Energy Flows Between Molecules
- We Are Consumers

We Reflect Our Environment: We Have a Habitat and a Niche 35

- Habitats Have Limitations
- Humans Are Animals

CHAPTER PLANNER

- ❑ Study the picture and read the opening story.
- ❑ Scan the Learning Objectives in each section: p. 24 ❑ p. 31 ❑ p. 35 ❑
- ❑ Read the text and study all figures and visuals. Answer any questions.

Analyze key features

- ❑ What a Scientist Sees, p. 28
- ❑ I Wonder..., p. 29
- ❑ Ethics and Issues, p. 30
- ❑ Process Diagram, p. 31
- ❑ Biological InSight, p. 36
- ❑ Health, Wellness, and Disease, p. 37
- ❑ Stop: Answer the Concept Checks before you go on: p. 30 ❑ p. 35 ❑ p. 38 ❑

End of chapter

- ❑ Review the Summary and Key Terms.
- ❑ Answer the Critical and Creative Thinking Questions.
- ❑ Answer What is happening in these pictures?
- ❑ Answer the Self-Test Questions.

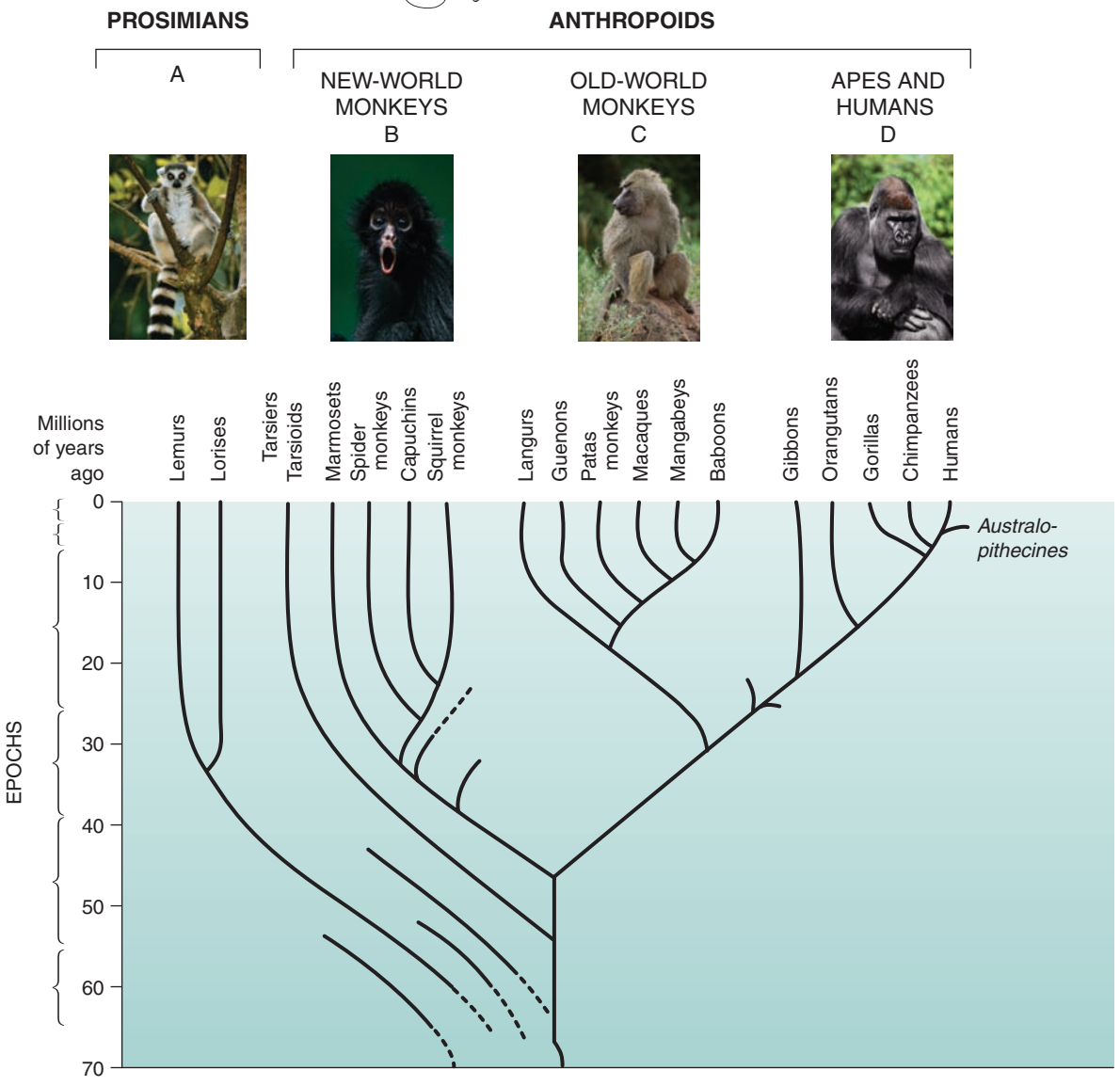
2.1 What Are the Origins of Modern Humans?

LEARNING OBJECTIVES

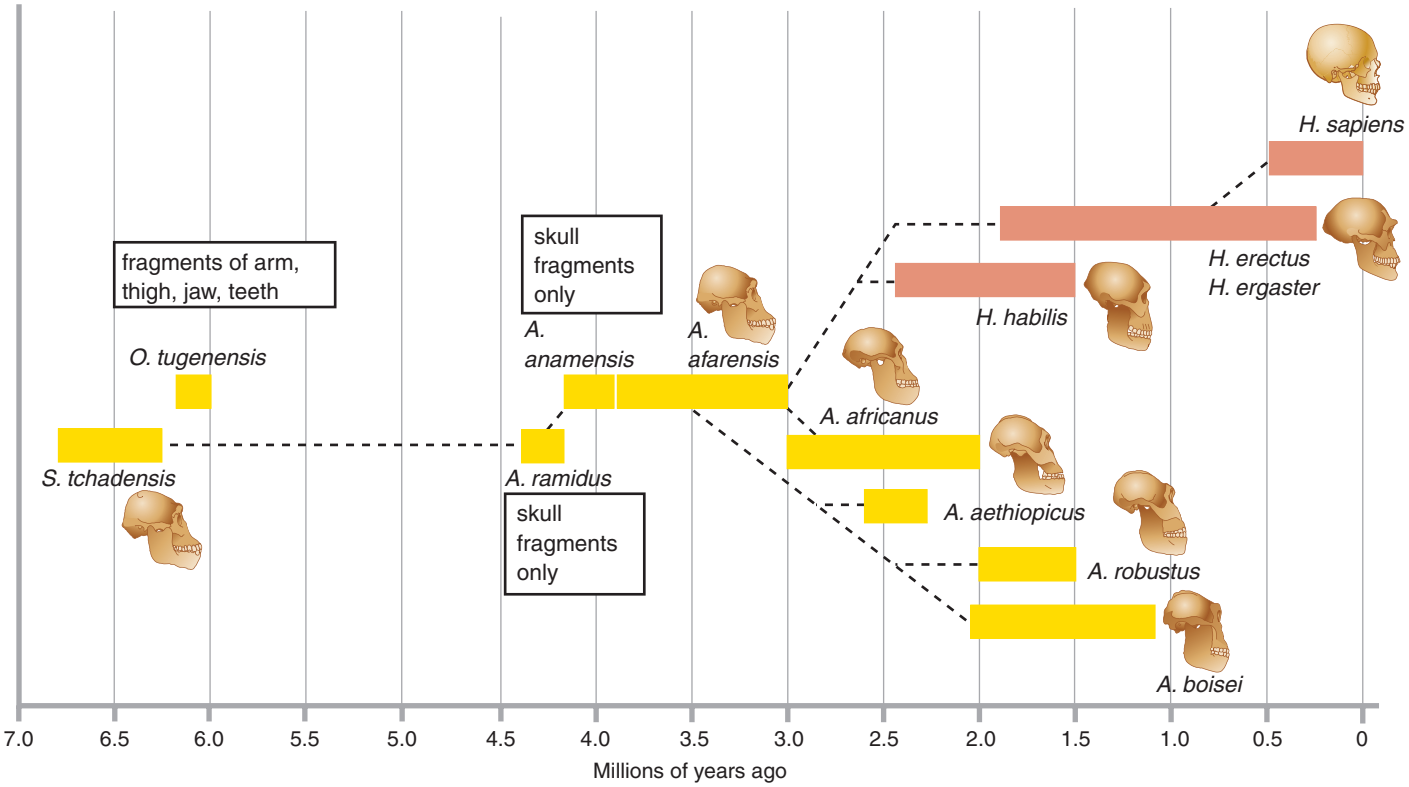
1. **Describe** the origins of modern humans.
2. **Describe** the characteristics of primates.
3. **Differentiate** *Homo habilis*, *Homo erectus*, *Homo neanderthalensis*, and *Homo sapiens*.
4. **Appreciate** the variety in modern humans.
5. **Discuss** the evolutionary forces currently affecting the human population.

In Chapter 1, we learned the taxonomic classification of humans: We belong to the class Mammalia, which also includes whales, dogs, squirrels, and bears. We are further separated into the order Primates, along with lemurs, monkeys, and apes. Primates share a common ancestor that lived about 60 million years ago. The order is characterized by five-digit hands with an

The human family tree • Figure 2.1



A closer look at the human family tree • Figure 2.2



opposable thumb, fingernails and toenails rather than claws, and **stereoscopic vision** with forward-facing eyes. All of these shared characteristics were adaptations to life in the trees. Our opposable thumb was a great evolutionary advance, allowing us to grasp firmly yet with precise control.

opposable thumb
A thumb that can move across the other four digits.

stereoscopic vision
Three-dimensional vision created by two slightly different views superimposed on one another.

Twenty-five million years ago, the ancestor of apes and humans diverged from the ancestors of old-world monkeys, as shown in **Figure 2.1**. Apes and humans are larger and have larger brains and smaller tails than monkeys. Our tails are so small, in fact, that they are not visible outside the body. Apes and humans are further distinguished by their complex social interactions. Comparisons of the structures of molecules found in all apes and humans indicate that gibbons diverged first, followed by orangutans, gorillas, chimpanzees, and humans. To be clear, we did not develop from a chimpanzee, but rather chimpanzees and humans diverged most recently from a common ancestor that probably looked something like a chimpanzee.

Continuing with the human taxonomic classification, we belong to the genus *Homo*, with the species epithet *sapiens*. As we noted earlier, *Homo sapiens* are unique in that they possess an upright **bipedal** stance, an opposable thumb, an enlarged brain case, and the capacity for complex speech communication. The fossil record contains many other *Homo* species, each carrying this unique combination of four characteristics with slight modifications. These modifications define the various hominid species and allow the different species to thrive in diverse areas of the world. Although scientists are still debating the specifics of human evolution, most agree on the basic pathway: that humans evolved in Africa when a primate began to walk upright as its usual form of locomotion. The process by which these changes in human form occurred is discussed in greater detail later in this book, after we take a look at genetics and heredity. See **Figure 2.2** for more of the human family tree.

bipedal
Two-footed rather than four-footed.

Omo I and Omo II skull fragments • Figure 2.3

The Human Ancestors Are Dead Twigs on the Family Tree

How long have *Homo sapiens* walked the Earth? In February 2005, new dating techniques were applied to human fossil remains found in 1967 by Richard Leakey. The critical skull findings are shown in **Figure 2.3**. These fossils included some bones and two skulls Leakey uncovered on opposite sides of the Omo River in Ethiopia. At the time of the finding, the two fossils were dated at 130,000 years old. Recent evidence suggests that they are in fact much older. Scientists now believe these two fossils to be the oldest known human remains. Omo I and Omo II, as the fossils are called, date the emergence of modern humans in Africa to 195,000 years ago.

The genus Homo was preceded by even earlier versions of man. *Australopithecus* was the first member of the family Hominidae. This organism walked upright, and its **cranium** was slightly larger than that of previous, nonhuman primates. Interestingly, the first hominid was an omnivore, eating both plant and animal foodstuffs, and was relatively small in stature. A second Australopithecine, *A. afarensis*, was slightly larger and, based on dentition, ate like a modern vegetarian. These organisms showed social behaviors and **sexual dimorphism** similar to the apes.

cranium Brain case, or skull.

sexual dimorphism Morphological differences between the two genders.

About 3 million years ago, *Homo habilis* appeared to share the planet with *A. afarensis*. This organism had a larger brain than *A. afarensis*, new types of teeth allowing it to eat a more varied diet, and perhaps the ability to make and use tools. *Homo habilis* literally means "handy man," and many of the *H. habilis* fossils are surrounded by stones that could be primitive tools.

Almost 2 million years ago, another speciation event produced *Homo erectus* and *Homo ergaster*. Lighter and more graceful than *H. habilis*, these organisms can be classified as humans, for they had subtle differences in cranial capacity, stature, and gait, as shown in **Figure 2.4**. Originally, these two were classified together as *H. erectus*. *H. ergaster* was distinguished in 1994, when scientists discovered that their skulls were different. *H. ergaster* has a high skull bone, thin cranial bones, a slim brow ridge, and a generally lighter skeleton than *H. erectus*. Both had a swift gait; long, muscled limbs; narrow hips; and body proportions like those of modern tropical humans. Sexual dimorphism was effectively lost in this group, indicating that both males and females probably participated in the same societal activities. Infant development was extended, allowing a longer family period for passing on learned traits and culture. These primates continued to make hunting tools and eating equipment.

A comparison of the skeletons of apes and *Homo erectus* • Figure 2.4

Although scientists are not clear on the exact date, it appears that *Homo erectus* and *H. ergaster* migrated out of Africa approximately 1 million years ago, and began to populate other continents. *H. erectus* may have left Africa to avoid environmental changes during an ice age. They remained a part of the biota of Java as recently as 500,000 years ago, making them contemporaries of modern *Homo sapiens*.

We have all heard of Neanderthals. Some scholars believe these hominids evolved as a separate species from *H. erectus*. Others think *H. erectus* first evolved into a form that was very close to modern humans, which then gave rise to both modern humans and Neanderthals. Are Neanderthals and modern humans related closely enough to be subspecies of *Homo sapiens*? In 1964, this was the accepted wisdom, based on anatomical similarities. Apparently, the two existed on the Earth at the same time, as indicated by fossil sites in Israel, where geologic strata indicate that *H. sapiens* lived at that location before *H. neanderthalensis*. Not much is understood of the interactions between these two species. It may be that they co-existed peacefully. Their phenotypes are remarkably similar (see **Figure 2.5**). Theories of Neanderthal extinction are based upon these potential interactions, and include competitive exclusion, genocide, and interbreeding.

Homo Sapiens Appears and Starts to Change Everything

It is difficult to pinpoint the exact beginning of *Homo sapiens*. Some scientists believe that all modern humans came from one small population in Africa that splintered, migrated, and populated the globe. This splintering must have happened approximately 140,000 to 100,000 years ago. Wherever *H. sapiens* appeared, they replaced all other hominids. We cannot be certain why, as the fossil record gives no indication of violence between species of hominids, nor does it provide evidence of disease. Did *H. sapiens* really fight and kill Neanderthals? Did Neanderthals fall victim to viruses that did not harm *H. sapiens*? Did Neanderthals breed with *H. sapiens*, eventually losing their characteristics as their genes were diluted in the larger *H. sapiens* gene pool? The questions are tantalizing, but we may never know their answers.

Neanderthal versus modern man • Figure 2.5

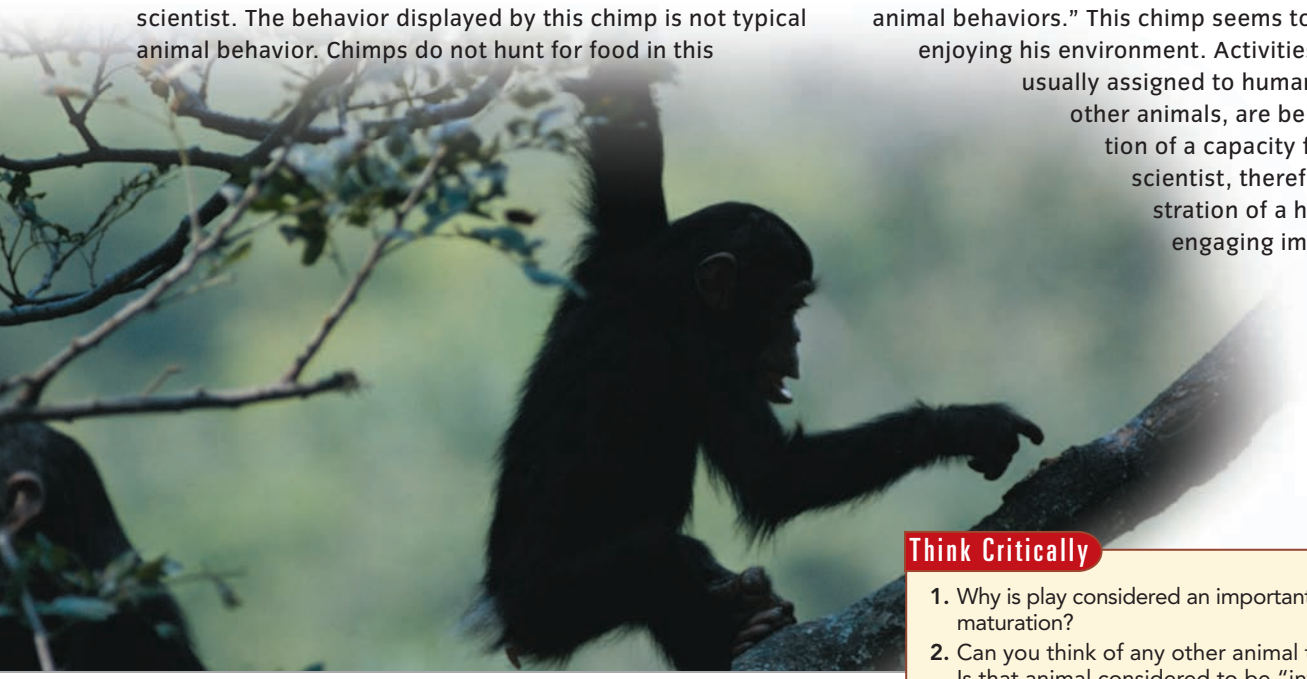
This image allows a direct comparison of the facial features of Neanderthals on the left and modern *Homo sapiens* on the right.

WHAT A SCIENTIST SEES

THE PLANNER

A Chimp at Play

While this picture may seem to be an interesting snapshot of a chimp to you and me, it is far more to a scientist. The behavior displayed by this chimp is not typical animal behavior. Chimps do not hunt for food in this manner, and this behavior does not indicate territorial protection, mate selection, or any of a number of other "base animal behaviors." This chimp seems to be investigating and enjoying his environment. Activities such as these are usually assigned to humans, and when seen in other animals, are believed to be an indication of a capacity for abstract thought. A scientist, therefore, sees the demonstration of a higher intellect in this engaging image.



NATIONAL GEOGRAPHIC

Think Critically

1. Why is play considered an important part of human maturation?
2. Can you think of any other animal that engages in play? Is that animal considered to be "intelligent?"

Human population differences and ethnicity are tangled concepts. The bottom line on the evolution of humans is that we are all one species. Do we look different? Yes, we do look a bit different, as seen in **Figure 2.6**. Humans have subtle physical differences that are heritable and that are usually associated with one group of people.

For almost all of our history, human populations were small, and isolated by geographic barriers such as forests, deserts, oceans, rivers, and mountains. During this isolation, **natural selection** and other mechanisms of population change, such as sexual selection, favored different genetic traits in the various populations. These differences formed what we used to call racial differences, including skin color, hair color, hair texture, eye shape, and body stature. Some of these traits developed as selective advantages in local environments. Dark skin offers better protection against UV light, and yet it is a disadvantage in Northern latitudes because the available sunlight is needed for the skin's production of vitamin D. Facial features, hair texture, and even blood types may have developed in response to environmental pressures.

natural selection
A natural process that favors individuals better adapted to the environment, ensuring that those traits are passed to the next generation.

However, these subtle differences can be overblown and used as a tool of oppression rather than of understanding. As a concept, the scientific validity of human races is question-

Human variation • Figure 2.6

This group of ethnically diverse school children exemplifies the many different phenotypes, or appearances, now found in the human population.

able at best. We now know that people can have more genetic differences with their nearest neighbors than with people living on other continents. The *Ethics and Issues* box discusses another facet of human inheritance: human nature.

As early hominids populated the Earth, they adapted to their environment. See *I Wonder… How Are Fossilized Human Remains "Interpreted" to Produce Our Family Tree?* for a look at how hominid adaptations have been studied. We now understand that just as the environment can change us over time, we humans are able to change the environment. How substantial are those changes? What sort of force do humans exert on the environment? To understand our role in the environment, we must study the environment itself. How do we interact with other organisms? What is our role in the biosphere? See *What a Scientist Sees* for a look at this sort of study. To begin this thought process, we will quickly take a look at how humans fit in our environment. In the last chapter of the text, we will place humans in the ecosystem by looking at the science of ecology.

To help keep the idea of humans in the environment in mind, this book is arranged into five units. Each unit covers a different aspect of human survival in the environment. Unit One introduces the science necessary to study this field. Unit Two describes how humans move through their environment. In Unit Three, we discuss the ways humans protect themselves from the hazards of the environment. It is obvious that humans are successful as a group, and Unit Four discusses the methods we use to thrive in our ecosystem. The final unit, Unit Five, discusses populating and affecting the environment.

I WONDER...

THE PLANNER

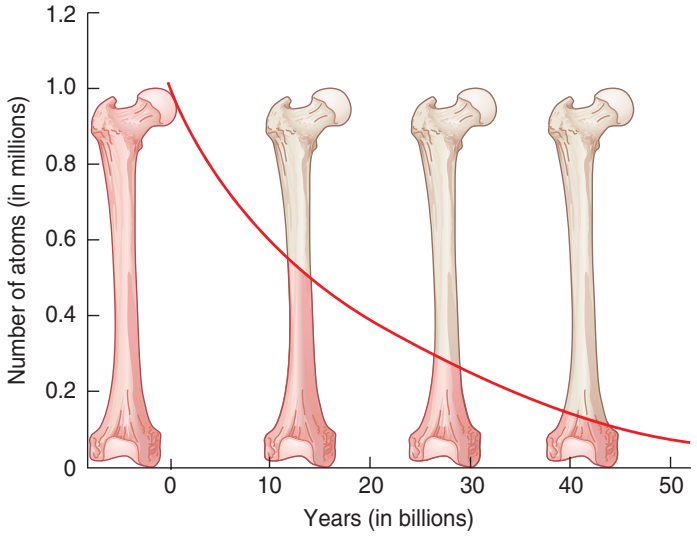
How Are Fossilized Human Remains "Interpreted" to Produce Our Family Tree?

When an archaeologist stumbles across a new set of hominid bones, questions arise. Are these bones from a hominid form already identified? Do they represent a "missing link" in our understanding of the evolution of modern man?

Naturally the fossil has to be correctly identified as hominid first. The key to hominid classification lies in the skull. The size and position of the brain case, the angle of the forehead, the prominence and shape of the brow line, the placement of the teeth, the size and shape of the nasal openings, and the size of muscle attachment sites are used to determine hominid status.

Once the fossil is accepted as hominid, it must be dated. Returning to field collections, archeologists and assistants will scour the surrounding sediment layer for clues leading to the age of the sediment, the type of vegetation present in that layer, and other indications of the prehistoric environment.

Radioactive dating is used to determine just how long a fossilized bone has been dead. A living bone, within a living organism, continues to grow and incorporate radioactive ions such as carbon 14 or U-238 from the environment into its matrix. These ions are incorporated in the same ratio as they exist in the natural environment. When an organism dies, the radioactive ion count in its skeleton is fixed. Over the years, as the bone ages, the radioactive elements decay, or lose radioactivity, at a known rate. Dating hominid fossils requires the use of a few different radioactive compounds. C-14 data can be used to date fossils from 55,000 years to the present. Determining the amount of uranium-238 decomposition can accurately date fossils that are from 55,000 to 300,000 years old. In even older fossils, from 2 to 3 million years old, the soil where the fossils were found can be dated using argon-40 to argon-39 or argon to potassium decomposition.



ETHICS AND ISSUES

THE PLANNER

To What Extent Is Human Nature Inherited?

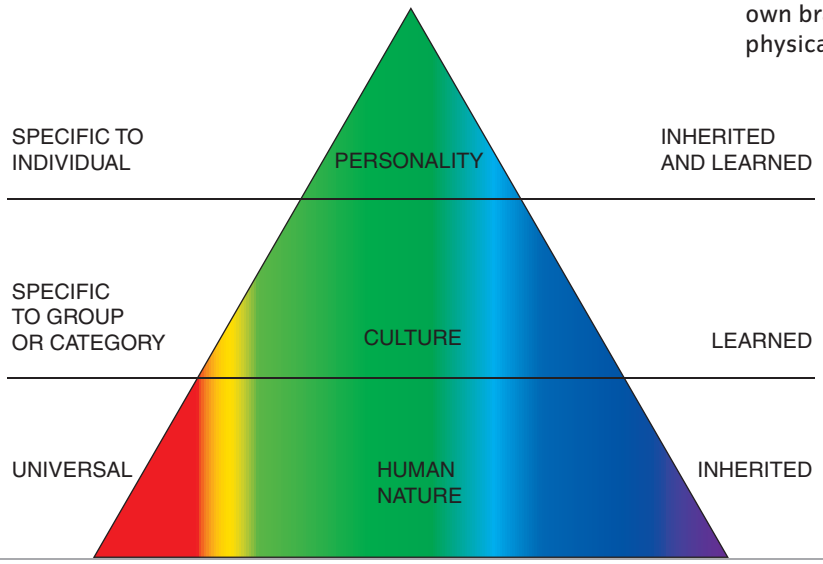
The "nature versus nurture" argument continues to ebb and flow. With the advent of evolutionary psychology, nature once again seems to have the upper hand. Winning popularity is the notion that there are mental and emotional characteristics that make us human, just as there are physical characteristics. Authors such as Edward O. Wilson, in *On Human Nature*, and Steven Pinker, in *The Blank Slate: The Modern Denial of Human Nature*, argue that human biology—the human genome—translates into human nature, a set of characteristics that are shared by all humans.

The notion that human nature is encoded in our genes makes many of us uncomfortable, however. Genetic differences can too easily be cast as racial or gender differences, and the concept of inherited human nature can too easily give way to *biological determinism*, the idea that biological factors are the root cause of everything we do. This belief, in turn, can lead us down the slippery slope to discrimination and even *eugenics*, policies designed to eliminate individuals who are seen as inherently less worthy, such as individuals who are mentally or physically handicapped.

Wide variations in the behavior of individuals, ranging from one extreme to the other—from saint to sinner—seem to argue against the idea of an inherited human nature. Even identical twins are never completely identical. Yet the historical record of every culture is filled with examples of deeply seated human traits, from creation myths to expressions of love to mourning the dead. In every age and every culture, war and cruelty have been juxtaposed with compassion and caring.

Critical Reasoning Issues The argument between followers of Wilson and Pinker and those who argue against the notion of a species-wide human nature may be a *false dichotomy*. This term of logical argumentation refers to the framing of an issue strictly in terms of two poles—in this case, nature and nurture. When we consider an issue in such terms, rather than considering possibilities that fall along a continuum from one pole to the other, we may find outselves falling into a logic trap.

Seeing the problem in terms of many variables rather than two can help disentangle a false dichotomy. In our example, the figure of a pyramid suggests that human nature and culture build on each other. Thus, human beings have certain underlying traits (1). Cultures mold those traits in ways appropriate to a particular culture (2), thereby creating their own brand of social cohesion and adapting to their unique physical and social environments. For instance, many argue that American individualism is a product of the expansiveness and material richness of the North American landmass combined with humans' natural tendency to seek new experiences. Finally (3), individuals within a given culture display a combination of inherent and cultural traits in different ways because of their distinct individual personalities.



Think Critically

1. Can you think of other examples of false dichotomies?
2. Does the pyramid illustration imply anything about the relative importance of human nature and culture in forming a given individual?

CONCEPT CHECK STOP

1. **What** are the origins of modern humans?
2. **What** are the main characteristics of primates?
3. **How** do *Homo erectus*, *H. habilis*, *H. neanderthalensis*, and *H. sapiens* differ?
4. **What** are some examples of the variety that exists in modern humans?
5. **What** are the current evolutionary forces affecting the human population?

2.2 What Does the Human Body Have in Common with the World Around It?

LEARNING OBJECTIVES

1. **Define** ecosystem and relate energy and chemical cycling in the human to that of the ecosystem.
2. **List** the functions of the 11 body systems.
3. **Compare** producers and consumers.

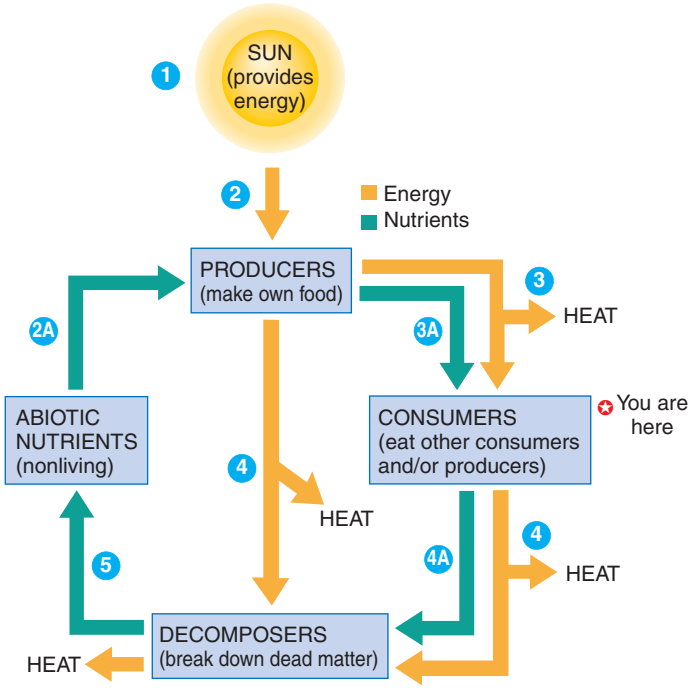
The term ecosystem is used frequently in **ecology** but is not often associated with human biology. However, the term provides an interesting and creative way to think about humans and their association with the environment. A scientist studying an ecosystem is studying the interactions between the living and the nonliving components of a defined area. In the field of ecology, that area is usually defined by physical parameters, such as precipitation, average temperature, and soil type. The human body follows many of the same laws as typical ecosystems. Both ecosystems and humans require energy, which flows through our bodies in much the same way it flows through traditionally defined ecosystems, such as the tropical rain forest. Similarly, humans and ecosystems display chemical cycling. **Figure 2.7** illustrates the typical energy flow and nutrient cycling of an ecosystem. Nitrogen cycles through the environment, passing from a gaseous state to a biologically useful state and then back to the gaseous state. In the human body, oxygen follows much the same route. It enters the body as a gas, attaches to red blood cells, and is transported to

ecology The study of the relationships among and between living and nonliving portions of the environment.

PROCESS DIAGRAM

THE PLANNER

Energy flow and resource cycling • Figure 2.7



In this image, energy from the sun travels through the producers, consumers, and decomposers, escaping the system as heat at each step. In contrast, the nutrients cycle through the organisms and abiotic segments of the biosphere. In this figure, humans are consumers.

1. Energy originates with the sun.
2. Energy is captured by producers, and converted to organic compounds available for consumers. Heat is lost in this process.
2a. Nutrients are taken from the nonliving portions of the environment to sustain producers.
3. Consumers eat both producers and other consumers, losing heat to the environment as they metabolize.
3a. Nutrients in the producer's bodies are passed on to the consumer, with very little loss.
4. Both producers and consumers die and are decomposed. The energy remaining in their bodies is lost again as heat, with no energy re-cycling to the sun.
4a. Nutrients in the consumer's bodies are passed on to the decomposers, with very little loss.
5. Nutrients are deposited in the abiotic portion of the ecosystem, where they are again available for the producers.

oxygen-poor areas of the body. The oxygen is then transformed into something useful to the cell. Oxygen leaves the body attached to biomolecules that are broken down, releasing the oxygen back into the atmosphere.

Energy Flows Between Molecules

This energy flow begins with the energy found in the foods we eat and ends with the energy stored in our tissues and released as heat from the surface of our bodies. As we consume food, we break down the molecules to release their energy. Using the digestive system (discussed in Chapter 15), we slowly oxidize food molecules. The smaller molecules are then taken into individual cells where the breakdown process continues. Cellular energy is stored as ATP, a high-energy molecule that serves as the energy currency for the body. Most of the food that we ingest must eventually be converted to ATP in order for our cells to function, as we will see in Chapter 3. This controlled burning of our food releases the energy of the molecules slowly, rather than releasing it in a sudden burst.

Fire is a familiar example of an uncontrolled release of energy. The molecules of fuel react with oxygen and heat to produce a sudden, intense release of the chemical energy stored in the fuel. Thankfully, our body has an entire system, complete with many different biochemical processes, that releases energy in a useful, less destructive form. We do not spontaneously combust. If we were to experience a sudden release of the energy of chemical bonds inside our bodies, the result would be similar to starting a fire.

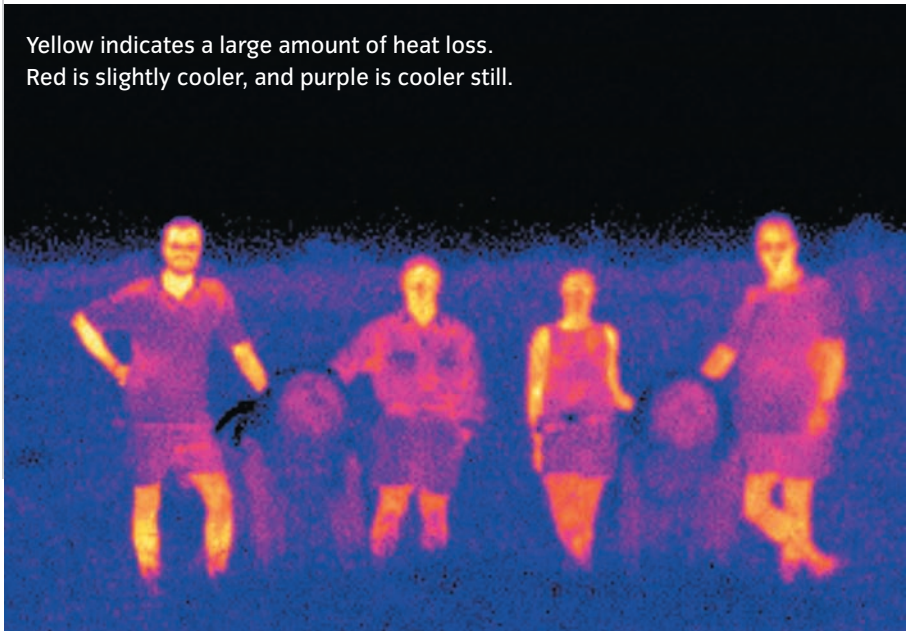
Not only do we slowly release energy to drive the processes of the body, but we also lose a good portion of that released energy, sending it directly back into the environment. If someone has been sitting in a chair and then leaves, the seat and back of that chair will feel warmer than those of a chair in which no one was sitting. People generate excess heat as they release energy. That heat is lost from the body through the skin. If the heat passes from the body to the surrounding atmosphere, it is referred to as radiation, and as that heat warms the surrounding air, the process is convection. However, if the heat energy passes directly to another solid object through physical contact, the transfer of energy is called conduction. Using an infrared camera, this loss of heat through radiation, convection, and conduction can be seen. Heat loss from the body can be visualized using specialized lenses as was done for **Figure 2.8**.

Unlike energy, which follows a one-way flow through the cells of the body, chemicals cycle. Chemicals are neither created nor destroyed by the body but are merely reorganized for specific uses. For example, calcium is a naturally occurring element that is essential for bone formation and muscle contraction. It is taken into the body in the food we eat. Once inside, calcium is pulled from its original molecules and added to the stores of calcium found in muscle cells and bone. If blood calcium levels are high enough, excess calcium is stored in the bones. If blood calcium levels drop, the calcium stored in the bones is removed and sent through the blood. When we die, our muscles and bones with their stores of calcium are broken down and the calcium returned to the soil. This cycle is the same for all of the main elements of the body. We get the elements from what we eat, use the elements for our own purposes, and return the elements when we are through with them.

Throughout this book, we will look at the physiological systems of the human body. Each of these can be thought of in terms of nutrient cycling and energy flow. Many of our body systems therefore function as ecosystems, having adapted over time to maintain our internal environment within narrow ranges so that our chemical cycling and our energy needs are not compromised.

There are parallels between what is happening in our bodies and what is happening in the world around us. **Table 2.1** indicates the systems we will cover, and gives a brief function for each. For example, the skeleto-muscular system discussed in Chapter 6 assists in the cycling of calcium within the body, and the respiratory system, the topic of Chapter 13, is responsible for the cycling of oxygen and carbon dioxide gases between our bodies and the environment. We are very good at recycling

Body thermal scan showing "aura" of heat radiation • Figure 2.8

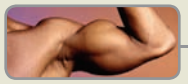
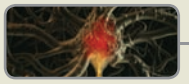
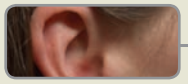
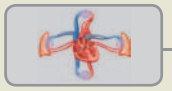
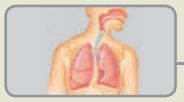
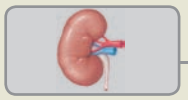


these gases—so good, in fact, that your next breath may contain oxygen that has passed through the body of William Shakespeare, Julius Caesar, or Cleopatra. We will find in Chapter 10 that we serve as host to a myriad of bacterial colonies, and our immune cells work to preserve that delicate balance between healthy host and preyed-upon nutrient source. As we cover the digestive system in Chapters 14 and 15, we will see direct parallels with energy flow through our bodies and through the ecosystem. In order to maintain our health, we must recycle and purify the fluid of our internal environment. The urinary system functions within our bodies in a fashion similar to the water cycle of the larger ecosystem: both cleanse and purify the aqueous environment. Our bodies use filtration and **secretion**, where the ecosystem uses condensation, evaporation, precipitation, and **percolation** to the same ends. The reproductive system ensures the survival of our species, just as recycling and intact energy chains ensure the survival of the ecosystem.

secretion In this sense, moving substances from the blood to the forming urine in the kidneys.

percolation Filtration through a porous substance.

The organ systems of the body and their functions Table 2.1

	System	Main Function
	Skeleto-muscular	Provide support and movement; store calcium
	Nervous	Receive and process information; formulate response
	Sensory	Receive visual, auditory, temperature, and tactile information
	Cutaneous	Provide barrier between self and environment; regulate temperature
	Lymphatic	Protect against specific diseases
	Cardiovascular	Pump nutrients, oxygen, carbon dioxide, and chemical messengers throughout body
	Respiratory	Cycle gases into and out of the body
	Digestive	Cycle nutrients through the body
	Urinary	Provide fluid balance and purification
	Endocrine	Regulate long-term changes
	Reproductive	Perpetuate the species

We Are Consumers

Organisms, and entire populations, can be classified as **producers** or **consumers**. Producers assemble usable food molecules through photosynthesis or (more rarely) chemosynthesis. Examples of producers are green plants and bacteria that live off chemicals emitted from oceanic thermal vents. Consumers cannot create food molecules but instead must obtain them from other organisms. Animals, whether they eat plants or other animals, are consumers. In the biological sense, this means that humans are consumers. We cannot manufacture our own food given only an energy source and raw chemicals. Like the rest of the animal kingdom, we rely on plants to provide nutrients in forms useful to us.

producers
Organisms that create their own nutrients from inorganic substances; mainly green plants.

consumers
Organisms that must ingest nutrients because they cannot manufacture their own.

Humans beings do produce, in one sense of the word. We take inorganic elements and combine them to produce new items. We smelt ore to create stronger metals, mine fossil fuels to provide different energy sources, melt rock to form glass, and smash atoms to release energy, creating different elements in the process. None of these activities can be defined as biological production, however, since they do not result in producing energy for our bodily needs.

Producers are autotrophic, meaning they carry out photosynthesis or chemosynthesis and make food for themselves. Producers do not eat like humans, or even like mosquitoes or dung beetles. The entire biosphere relies on producers to create organic fuel from the sun's energy. On land, green plants and **cyanobacteria** are the main producers. In freshwater

cyanobacteria
Blue-green, photosynthetic bacteria.

The four categories of consumer • Figure 2.9

Humans are omnivores, consuming everything from strawberries and lettuce leaves to beef and shark flesh.

a. The arctic hare is an herbivore, eating flowers and shoots to gain the energy stored in them.

b. The green anolis lizard is a carnivore, eating a grasshopper.

c. The pig eats both plant and animal matter, classifying it as an omnivore.

d. The fiddler crab is feeding on dead or decaying organic matter at the bottom of the ocean, making it a detritivore.

and marine ecosystems, algae and phytoplankton fill this niche. A few communities survive on chemical energy instead of solar energy.

Consumers are heterotrophs. Consumers cannot manufacture organic fuel with solar power but instead must ingest existing organic fuel. **Figure 2.9** illustrates typical consumers. The four types of consumer are classified by food source:

- **Herbivores** eat green plants. They get their energy directly from the producer. Because they feed directly on autotrophs, herbivores are also called **primary consumers**. Herbivores include bison, humans who are strict vegetarians, fish that graze on vegetation, and fruit- and grain-eating birds, such as parrots.
- **Carnivores** eat other animals and meet their protein and caloric requirements through this "complete" nutrition source. Carnivores usually eat less often and/or require smaller portions than herbivores. It does take more energy to be a carnivore, though, since herbivores do not have to waste energy chasing plants! Carnivores that feed on herbivores are called **secondary consumers**. If they feed on other carnivores, they may be **tertiary**—or rarely, **quaternary**—**consumers**.
- **Omnivores** are animals that can eat either plants or animals. The benefit of being an omnivore is that food can be obtained much more efficiently from both plant and animal sources. The human is an omnivore that can eat such bizarre and diverse foods as artichokes and lobster, and obtain nutrition from each.
- **Decomposers**, or **detritivores**, obtain their nutrients from **detritus**, returning most of the material to the soil. Decomposers don't get much respect, but bacteria, fungi, earthworms, and small soil organisms, such as nematodes and isopods, are essential to a healthy ecosystem. These organisms recycle dead plant and animal matter into nutrients that primary producers can use, ensuring that the limited resources of the ecosystem are available for reuse and that dead bodies do not pile up.

detritus Loose fragments of organic and inorganic matter obtained from decomposition and weathering.

CONCEPT CHECK STOP

1. **What** is an ecosystem and **how** is the human body similar to an ecosystem?
2. **What** are the functions of the eleven body systems?
3. **Why** do all ecosystems include a producer, a primary consumer, a secondary consumer, and a decomposer?

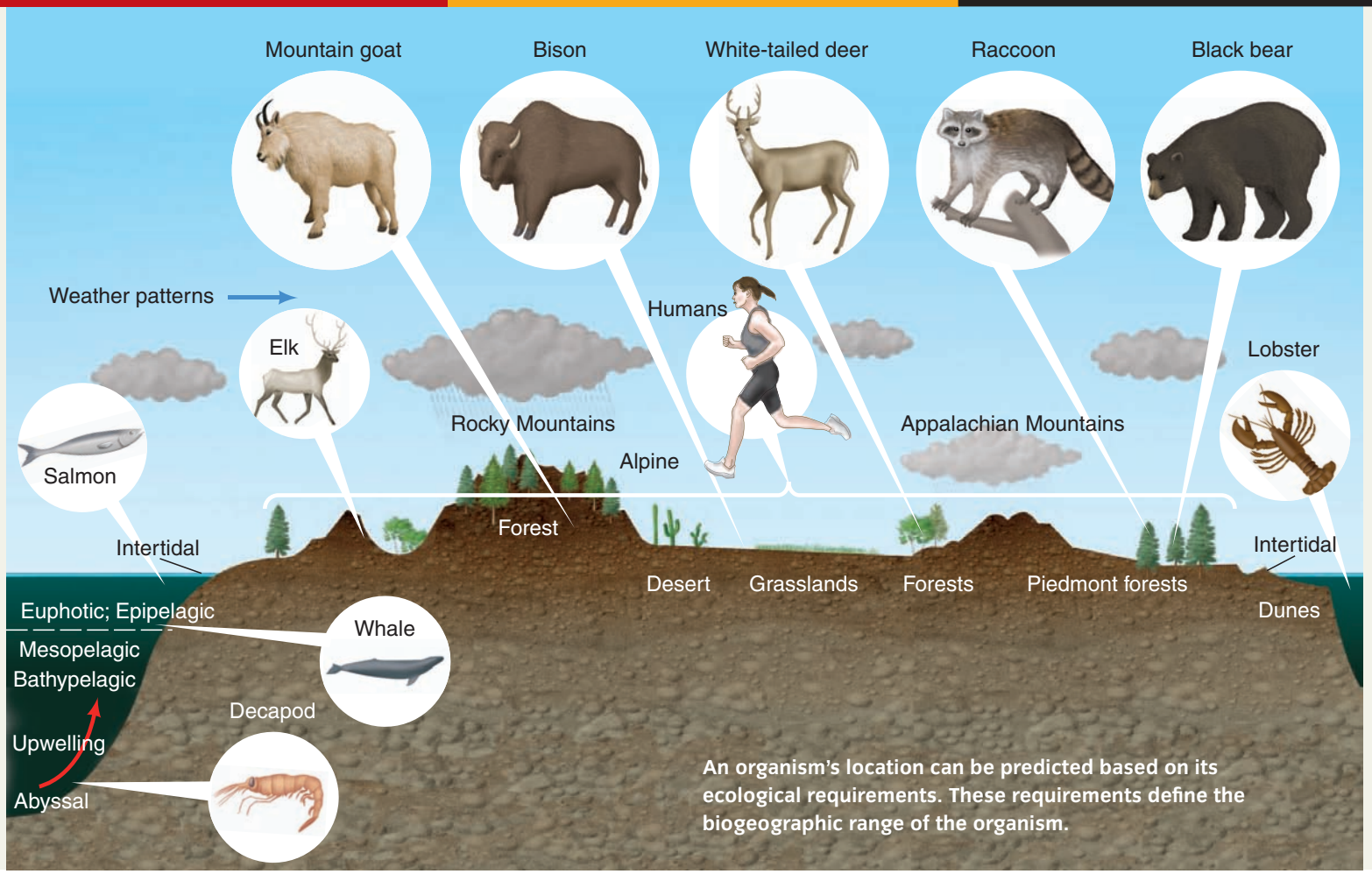
2.3 We Reflect Our Environment: We Have a Habitat and a Niche

LEARNING OBJECTIVES

1. **Define** habitat.
2. **Describe** the niche of an organism.

Two of the common descriptive terms used in the field of ecology are **habitat** and **niche**. These terms are used when discussing the interaction of individual organisms in populations, and groups of organisms in communities and ecosystems. Because humans are organisms living in the ecosystem, these terms apply to us as well.

Each of the organisms in a particular area has a specific habitat and niche. Habitat is loosely defined as the place where the organism lives. White-tailed deer can be found in deciduous forests in North America; adult green sea turtles can be found in near-shore waters of the Central Pacific; tsetse flies live in the low-lying rain forest and savannah of Africa. Assuming the habitat is large enough,



An organism's location can be predicted based on its ecological requirements. These requirements define the biogeographic range of the organism.

it is usually shared by many populations. Rabbits and field mice share grassy fields near forests. Polar bears and seals make the Arctic Ocean their habitat.

Habitats Have Limitations

Habitat is limited by physical obstacles and competition for resources. Physical obstacles can be obvious structures, such as mountain ranges, rivers, and deserts, or subtle variations such as salinity and density gradients in the open ocean or sunlight availability in the forest. Habitat limits create a geographic range of population distributions, called **biogeographic ranges**. Knowing the habitat requirements of any organism allows us to predict its location. Humans have habitat requirements as well. We do not survive well in the extreme cold of the polar ice caps, nor do we thrive in desert areas with little water and extreme thermal ranges. We don't thrive deep under the ocean or at the top of the highest mountains, so our vertical range is less than a dozen miles (**Figure 2.10**).

biogeographic range The expected geographic range of an organism, based on its habitat requirements.

However, humans often alter their habitat more than other organisms, creating livable space in areas that would normally be inhospitable. There are people making use of habitat on every continent except Antarctica. The United Nations Settlement Program, UN-HABITAT, produces periodic global reports on human settlements, monitoring our use of habitat across the planet. Although this department focuses on finances associated with housing the human population, it does also provide a scientific look at the use and misuse of habitat by our species. You can read the latest reports from this group online, and see for yourself just how adaptable humans are!

Niche defines the organism's "job," or role in the community. Everything from where an organism lives to what it eats to what time of day it is active helps define its niche. If you are a typical college student, your habitat is your campus. Your niche includes your dorm room, your class schedule, your extracurricular activities, your dietary choices, your study habits, and even your wardrobe. No two organisms can occupy the same niche in the same habitat. Imagine how difficult your existence would be if another student was following your exact schedule, living in your room, and eating the same food at exactly the same time! One of you would have to alter your routine in order to coexist.

Often we describe the niche of an entire species rather than of each individual. Individuals of a species utilize the same resources in the same fashion; therefore, we can speak of an entire species when we describe niche. Of course, individuals within species compete for resources, but a more global view would indicate that different species compete for niches, while individuals in that species share the resources of that niche. Although they are all using the resource at the same time and in the same fashion, enough resources remain to support the population.

Resource use may cause problems for the organisms. See *Health, Wellness, and Disease: Environmental Illness: Real or Imagined?*

HEALTH, WELLNESS, AND DISEASE

WILEY PLUS Video

Environmental Illness: Real or Imagined?

THE PLANNER

Our natural environment can be the source of a number of acute illnesses and long-term or chronic diseases. Plants, insects, and even the sun cause danger to human beings. When people make changes to the environment—either the micro environment in which an individual lives or works or the macro environment in which we all live and work—there is a risk of potential illness and disease.

Many of the activities we undertake daily cause pollution of various sorts. Fertilizers, herbicides, pesticides, and other compounds cause pollution of the soil and water. Paints, improperly vented space heaters, tobacco smoke, and the naturally occurring substance radon cause indoor air pollution. The burning of fossil fuels to create energy is the largest cause of outdoor air pollution.

The largest danger of both indoor and outdoor air pollution is chronic lung diseases, the most common of which is asthma. Scientific studies clearly link increased asthma rates with higher levels of air pollution caused by family members who smoke, as well as by transportation and manufacturing.

Los Angeles leads the country in the most days with low air quality; large industrial cities in the East and Midwest, such as New York, Philadelphia, Baltimore, Pittsburgh, and Chicago, also have high pollution indices and high asthma rates.

Pollution, however, is a natural outgrowth of modern living. Those who study disease, known as epidemiologists (we'll study more about them in Chapter 12), continue to believe that far less disease is caused by pollution than was caused in earlier years by poor hygiene and lack of modern technologies.

Humans Are Animals

As you can see, humans are animals similar to all the others on the planet. We occupy a niche, consume energy, produce waste, and evolve just like every other multicellular animal. We live in homeostasis, achieving a balance both within our bodies and outside, in our environment (most of the time!). Of course there are differences that set us apart. We have a unique biochemistry and a more developed brain than other animals. As we go through this text, it is important to keep in mind our place in the natural order of things. We are a product of the ecosystem, and as such fit into that order and balance. We are not, as quoted in the 1999 film *The Matrix*, a viral plague on the planet! However, sometimes we seem to disrupt that balance, as observed in *Health, Wellness, and Disease: Environmental: Illness: Real or Imagined?* on page 37.

CONCEPT CHECK STOP

1. **What** is a habitat?
2. **What** are the characteristics of the niche occupied by a typical family dog?

Summary

THE PLANNER

1 What Are the Origins of Modern Humans? 24

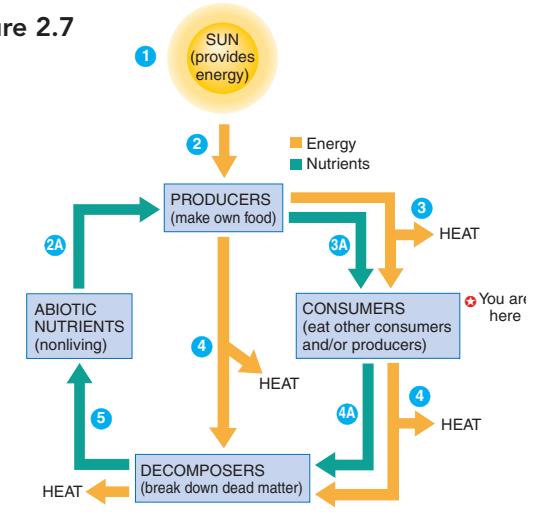
- Humans are mammals, with five-digit hands and an opposable thumb, stereoscopic vision, and bipedal locomotion. We belong to the genus *Homo*, with our enlarged brain case and our capacity for complex speech communication.
- There have been many types of hominid organisms on Earth, including *Australopithecus, H. erectus, H. ergaster,* and *H. neanderthalensis*. Each of these had slightly different characteristics, and none are currently walking the planet. *Homo sapiens* is the only extant member of the genus *Homo*.
- Although we recognize different ethnic populations, such as those seen here, all humans are the same species. Our ethnic differences are merely naturally selected traits that became prevalent in subpopulations of humans over time. These differences should begin to disappear as intraglobal travel becomes more common.

Figure 2.6

2 What Does the Human Body Have in Common with the World Around It? 31

- Just like an ecosystem, the human body is a study in interactions. We require energy, and chemicals cycle through our bodies just as they do through the larger environment. Energy follows a one-way flow, whereas chemicals are caught in cycles of use and transfer.
- The systems of the body all play vital roles in maintaining humans in the environment. Table 2.1 gives a brief overview of these systems and their functions.
- As you can see in this flow chart, producers are autotrophic—in other words, they fix compounds and provide nutrients for consumers. Consumers cannot fix compounds and are therefore heterotrophs. They must obtain energy from the producers. Consumers that eat producers are referred to as primary consumers. Those that eat primary consumers are secondary consumers.

Figure 2.7



- Consumers can be described as herbivores, carnivores, omnivores, or detritivores.

3 We Reflect Our Environment: We Have a Habitat and a Niche 35

- Habitat describes the area in which an organism lives, while niche more closely describes that organism's activities and resource use. Habitat, as shown here, is defined by physical parameters, such as mountain ranges or salinity differences. Humans are capable of altering their environment, thus extending their usable habitat.
- No two organisms can occupy the same niche at the same time. Resources in the environment are limited, therefore organisms compete for them. This competition helps to define the organism's niche.

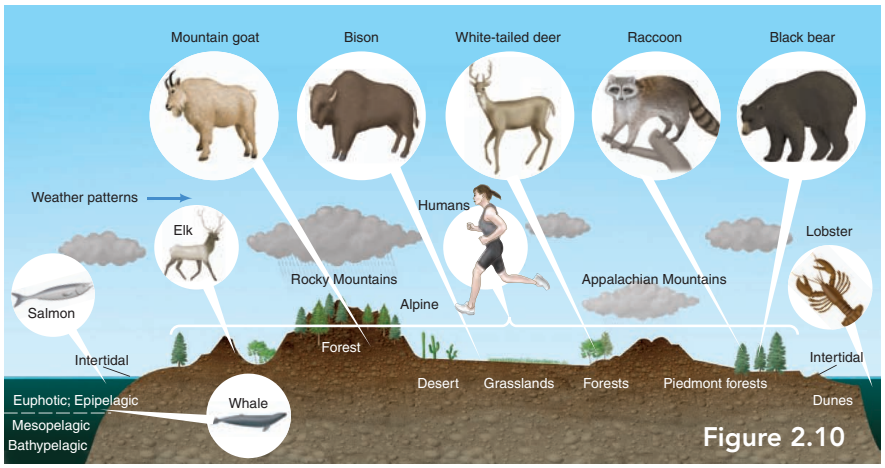


Figure 2.10

Key Terms

- biogeographic range 36
- bipedal 25
- consumers 34
- cranium 26
- cyanobacteria 34
- detritus 35
- ecology 31
- natural selection 28
- opposable thumb 25
- percolation 33
- producers 34
- secretion 33
- sexual dimorphism 26
- stereoscopic vision 25

Critical and Creative Thinking Questions

1. List the four unique characteristics that define the genus *Homo*. What survival benefit does each one impart?
2. Humans have a great effect on the evolution of other organisms. What activities do we engage in that directly affect that evolution? How do humans affect our own changes over time?
3. Think about your personal habitat and niche. What is the typical habitat of a human? Describe the niche of *Homo sapiens*.
4. **CLINICAL CLICK QUESTION**
   A new school has been needed for many years in Jerry's community. It is finally being built, but there is a problem. In digging the foundation for the main building, what appear to be ancient human remains have been unearthed. What would you, as a science advisor, do in this situation? Check this news clipping for information: http://www.lehighvalleylive.com/newsflash/index.ssf?/base/national-50/1250893764237320.xml&storylist=technology You decide that excavation work must be stopped while archaeologists are called in. Jerry and his neighbors are angry that a few "old bones that may or may not even be human" are standing between their children and a good education. What would you say to this community to help them to understand what must be done next? Can you explain to the affected constituents what it is that these archaeologists will be doing? Visit the eHow Web site http://www.ehow.com/how_2065469_perform-archaeological-dig.html to help you prepare your speech.

What is happening in these pictures?

Adaptation to environmental stresses occurs all the time. In these parallel images, one group of people has adapted to the extreme cold of their environment, needing little additional protection from the temperature. The other group of people has not adapted as well, requiring thicker insulating layers.

Think Critically

1. What environmental factors might cause this difference in adaptation?
2. What role do differing cultural practices play in human adaptation to extreme cold?

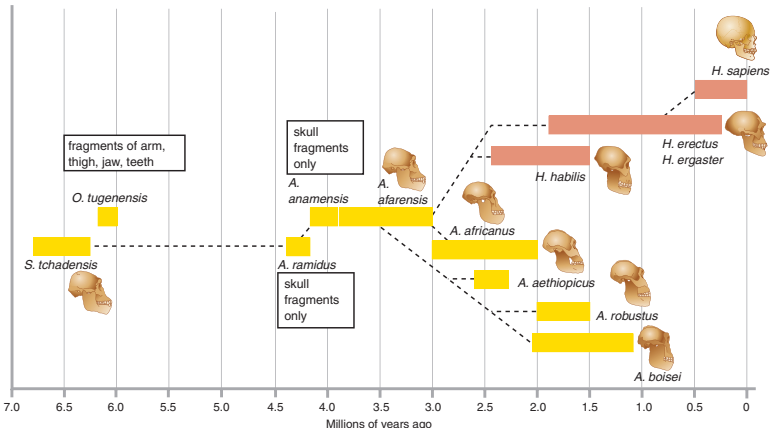
Self-Test

1. The first member of the family Hominidae that has been identified from more than a skull fragment is _____.

   a. *H. sapiens*
   c. *A. afarensis*
   b. *H. habilis*
   d. *S. tchadensis*

2. As shown in this figure, the species of man that has the longest survivorship thus far is _____.

   a. *H. sapiens*
   b. *H. erectus*
   c. *H. habilis*
   d. This information is not given on the figure.



3. In this image, you can see _____ different species of human.

   a. 1
   c. 4
   b. 2
   d. 7

4. The significance of the skull fragments, shown on the next page is that _____.

   a. they can be identified as human
   b. they represent the missing link that gave rise to the genus *Homo*
   c. they helped us correctly date the emergence of modern man
   d. the finding of these skull fragments proved that Leakey was correct in his estimate of the age of man

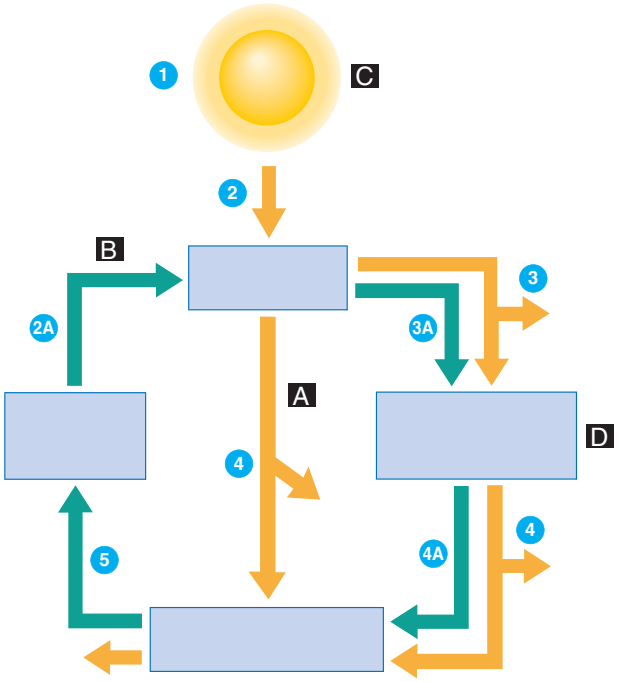
5. *Australopithecus* showed both social behaviors and sexual dimorphism.
   a. true b. false

6. The lighter, more graceful hominids that evolved after *Homo habilis* were _____.
   a. *Homo erectus*
   b. *Homo ergaster*
   c. *Homo sapiens*
   d. All of the above evolved after *H habilis*.

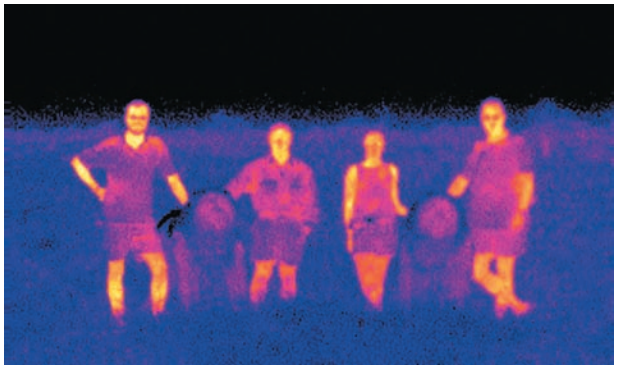
7. *Homo erectus* were never contemporaries of *H. sapiens*.
   a. true b. false

8. *Homo sapiens* appeared as a group that had splintered off of the original hominid population approximately _____.
   a. 140,000 to 100,000 years ago
   b. 195,000 years ago
   c. 500,000 years ago
   d. Scientists have no idea when this splintering might have taken place.

9. In this diagram, the section that indicates nutrients is labeled _____.
   a. A b. B c. C d. D



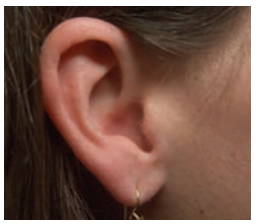
10. This image gives a vivid example of _____.
    a. the loss of energy as heat from our bodies
    b. the recycling of oxygen through our bodies
    c. the one-way flow of chemicals through our bodies
    d. the cycling of energy through our bodies



11. The function of the skeleto-muscular system is to _____.
    a. support and provide movement
    b. circulate nutrients, oxygen, carbon dioxide, and chemical messengers throughout the body
    c. regulate long-term changes
    d. protect against disease

12. The system that functions to regulate fluid balance and purification is the _____.
    a. endocrine system c. lymphatic system
    b. reproductive system d. urinary system

13. The system indicated by this photo is the _____.
    a. cardiovascular system
    b. sensory system
    c. respiratory system
    d. reproductive system



14. A pig can be classified as a(n) _____.
    a. herbivore c. omnivore
    b. carnivore d. detritivore

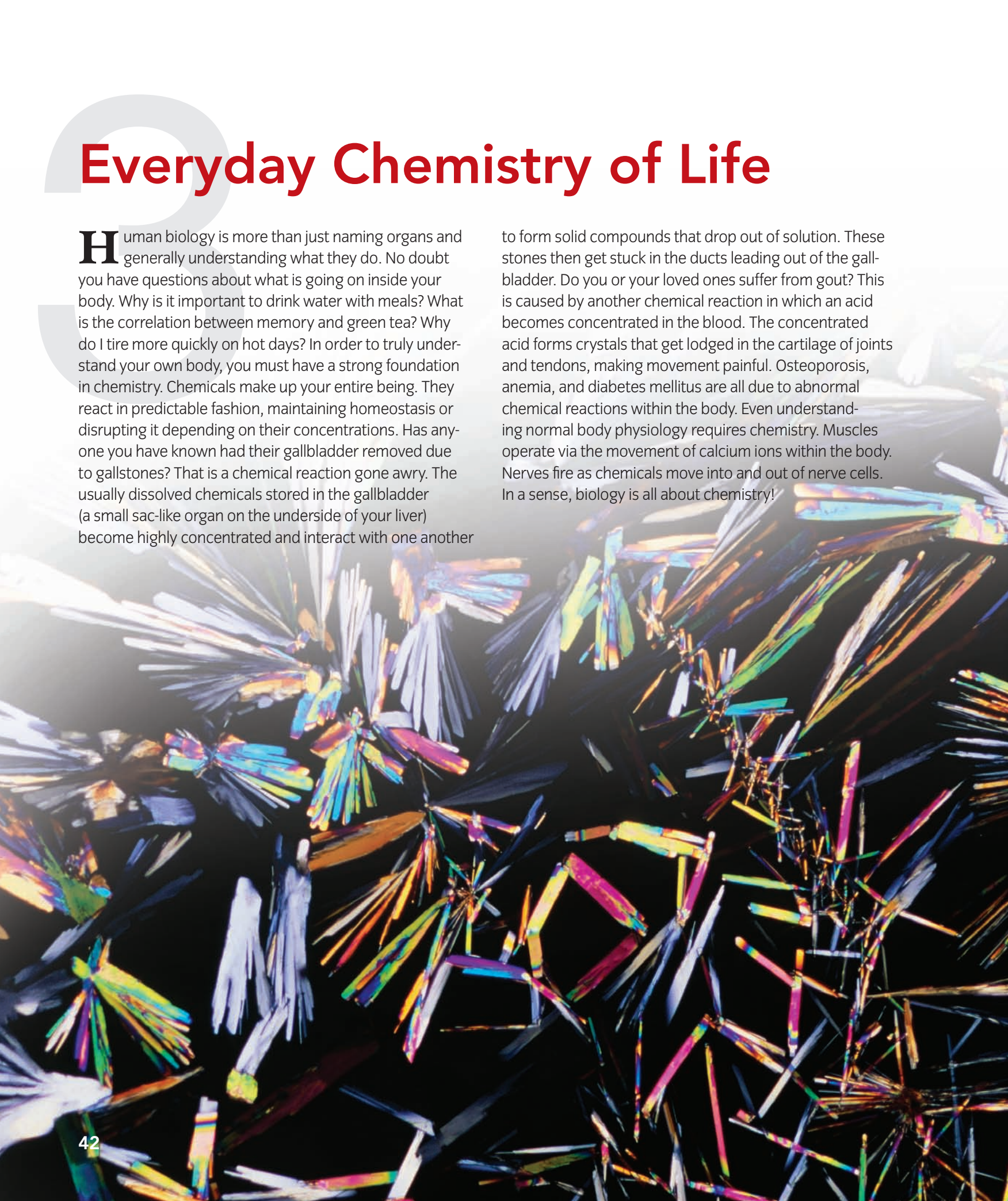
15. The organisms that are responsible for fixing the organic compounds used by the rest of the food chain are referred to as _____.
    a. consumers c. producers
    b. cyanobacteria d. heterotrophs

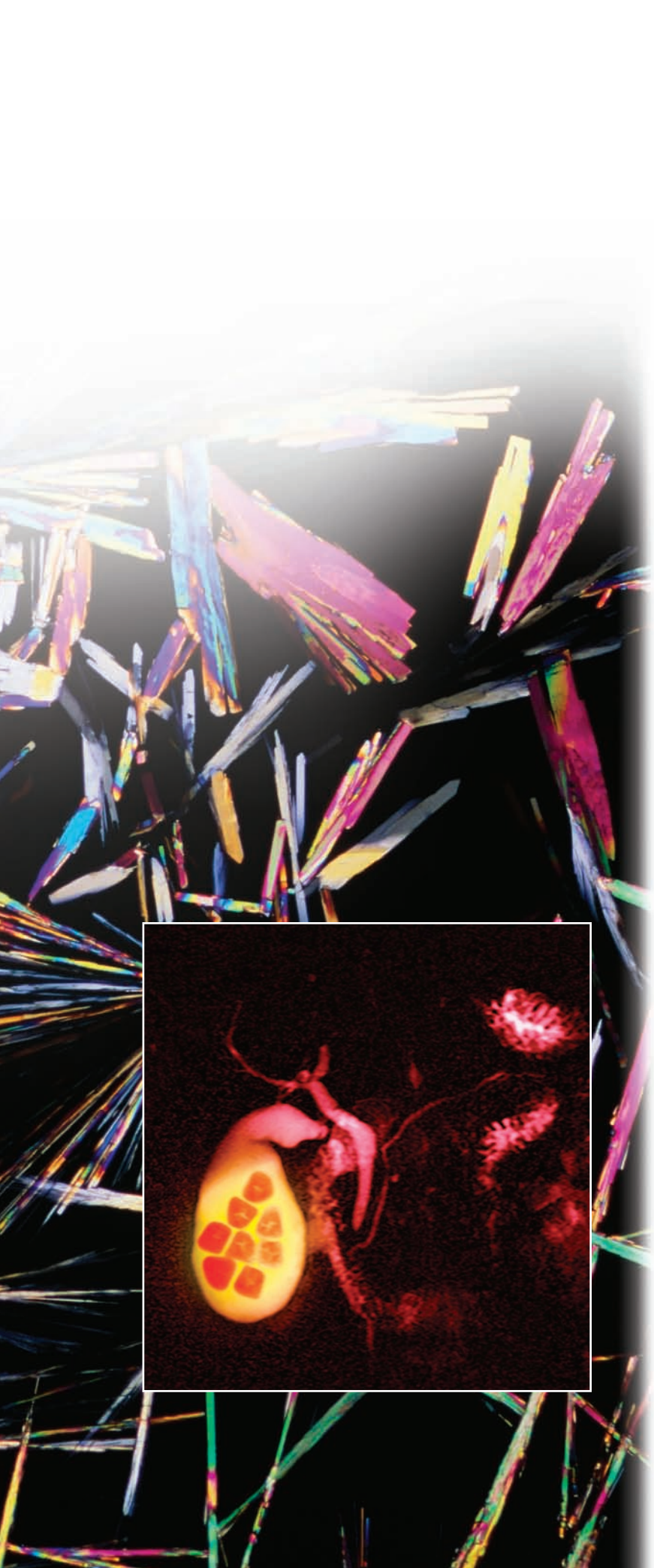
THE PLANNER

Review your Chapter Planner on the chapter opener and check off your completed work.

Everyday Chemistry of Life

Human biology is more than just naming organs and generally understanding what they do. No doubt you have questions about what is going on inside your body. Why is it important to drink water with meals? What is the correlation between memory and green tea? Why do I tire more quickly on hot days? In order to truly understand your own body, you must have a strong foundation in chemistry. Chemicals make up your entire being. They react in predictable fashion, maintaining homeostasis or disrupting it depending on their concentrations. Has anyone you have known had their gallbladder removed due to gallstones? That is a chemical reaction gone awry. The usually dissolved chemicals stored in the gallbladder (a small sac-like organ on the underside of your liver) become highly concentrated and interact with one another to form solid compounds that drop out of solution. These stones then get stuck in the ducts leading out of the gallbladder. Do you or your loved ones suffer from gout? This is caused by another chemical reaction in which an acid becomes concentrated in the blood. The concentrated acid forms crystals that get lodged in the cartilage of joints and tendons, making movement painful. Osteoporosis, anemia, and diabetes mellitus are all due to abnormal chemical reactions within the body. Even understanding normal body physiology requires chemistry. Muscles operate via the movement of calcium ions within the body. Nerves fire as chemicals move into and out of nerve cells. In a sense, biology is all about chemistry!





CHAPTER OUTLINE

Life Has a Unique Chemistry 44

- Atomic Structure Is the Foundation of Life
- Chemistry Is a Story of Bonding

Water Is Life's Essential Chemical 51

- Six Properties of Water Are Critical to Life
- Hydrogen and Hydroxide Ion Concentration Affects Chemical Properties

There Are Four Main Categories of Organic Chemicals 54

- Carbohydrates Are the Best Energy Source for the Human Body
- Lipids Are Long Chains of Carbons
- Proteins Are Both Structural and Functional
- Most Nucleic Acids Are Information Molecules
- High-Energy Compounds Power Cellular Activity

CHAPTER PLANNER

- ❑ Study the picture and read the opening story.
- ❑ Scan the Learning Objectives in each section: p. 44 ❑ p. 51 ❑ p. 54 ❑
- ❑ Read the text and study all figures and visuals. Answer any questions.

Analyze key features

- ❑ I Wonder..., p. 44
- ❑ Biological InSight, p. 45 ❑ p. 62 ❑
- ❑ Health, Wellness, and Disease, p. 47
- ❑ What a Scientist Sees, p. 50
- ❑ Ethics and Issues, p. 58
- ❑ Process Diagram, p. 59
- ❑ Stop: Answer the Concept Checks before you go on: p. 50 ❑ p. 53 ❑ p. 63 ❑

End of chapter

- ❑ Review the Summary and Key Terms.
- ❑ Answer the Critical and Creative Thinking Questions.
- ❑ Answer What is happening in this picture?
- ❑ Answer the Self-Test Questions.

3.1 Life Has a Unique Chemistry

LEARNING OBJECTIVES

1. **Identify** the four most common chemicals in living organisms.
2. **Define** the relationship between valence electrons and atomic reactivity.
3. **Recognize** the structure of an atom and the difference between polar and nonpolar molecules.
4. **Briefly explain** the structure of the periodic table and the meaning of the numbers on it.
5. **List** the three types of chemical bond and compare their strengths.

Humans and the rest of the living realm are made of multiple chemicals, but four **elements** predominate: oxygen, carbon, hydrogen, and nitrogen. For every 1,000 atoms in our bodies, roughly 630 are hydrogen, 255 are oxygen, 95 are carbon, and 15 are nitrogen. We also contain small quantities of calcium, phosphorus and sulfur, sodium, chlorine, and magnesium. Although trace elements are less abundant in the body, some of them are necessary for life, such as iron, iodine, and selenium. Most of these trace elements are for sale at your local pharmacy, next to the multivitamins. However, they are needed in extremely small doses, minute traces in fact, so taking supplemental minerals will enhance bodily performance ONLY if your diet lacks them to begin with. *I Wonder… If I Take Ginseng, Will I Pass My Exams?!* presents information on the enhancing effects of natural supplements.

element A substance made entirely of one type of atom; it cannot be chemically broken down.

Atomic Structure Is the Foundation of Life

Elements are made of atoms, and atoms are mostly empty space. Atoms include a central nucleus with an ill-defined space surrounding it. A cloud of electrons resides in this space, orbiting the nucleus. The electrons stay in orbit through electrical attraction to the positive protons of the nucleus, as shown in **Figure 3.1**.

I WONDER...

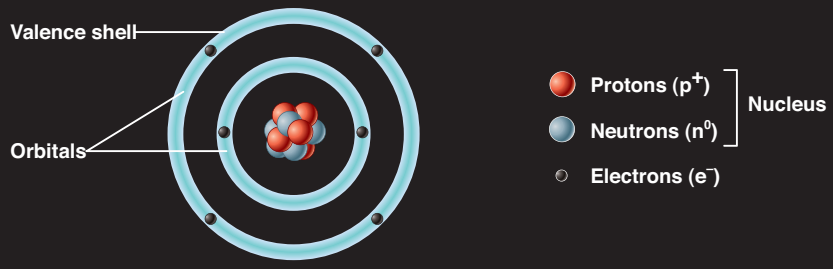
THE PLANNER

If I Take Ginseng, Will I Pass My Exams?!

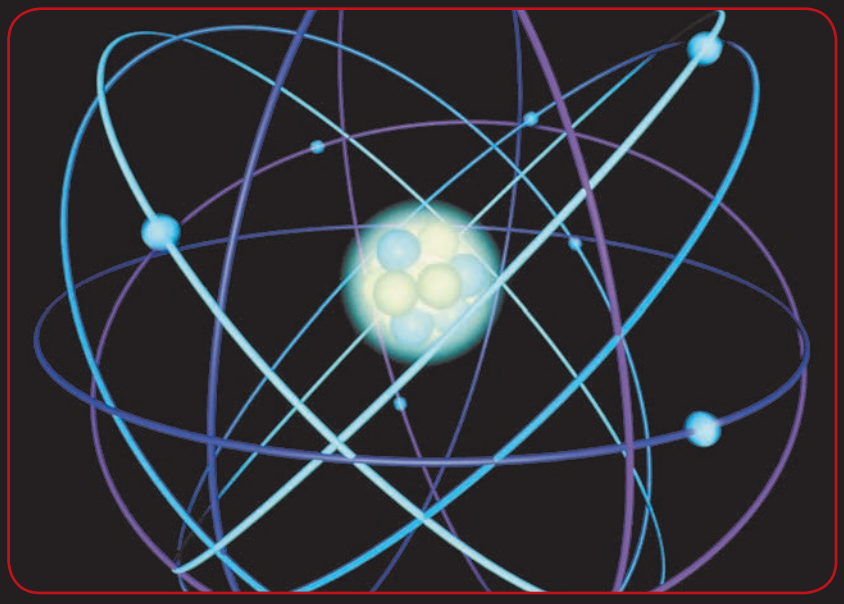
How many times do you walk into a room, only to stand there helplessly while you try to remember why you are there? How often do you study pages of notes, yet achieve disappointing results on the test? Maybe you can do something about that! Scientists are studying the effects of two herbs on brain chemistry: ginseng and *Ginkgo biloba*. Ginseng is thought to sharpen memory, and *Ginkgo biloba* is touted as a focus factor, increasing the ability to concentrate.

Ginseng comes from plants in the *Panax* genus. Interestingly, this genus name is derived from the Greek word for healing. Extracts from this plant have been used for centuries to alleviate stress, increase sexual interest, and stimulate cognition. However, while not completely dismissed, ginseng's ability to do any of these things has not been proven scientifically. In one study it seemed to enhance the perception of quality of life, but it did not improve simple learning in mice.

The compound called *Ginkgo biloba* comes from one of the oldest living plants, the maidenhair tree. Unlike the research on ginseng, scientific studies of *Ginkgo biloba* have shown that regular ingestion of *Ginkgo biloba* extract improves circulation and enhances blood flow to the brain. These effects improve neural functioning by increasing oxygen delivery to the brain. Recent investigations have been targeting a mixture of ginseng and *Ginkgo biloba* extracts. Initial results are promising, indicating that perhaps we can in fact increase our brainpower through chemistry. Now, that is smart!



Atoms have a central nucleus with orbiting electrons. The negatively charged electrons stay in place through electrical attraction to the positively charged protons. The outer shell of electrons determines the reactivity of the atom.



Although orbitals are usually drawn as simple circles, the actual path that electrons follow is not circular. Electrons do tend to stay in a specific three-dimensional area, however.

Oxygen (O) **Hydrogen (H)** **Carbon (C)** **Nitrogen (N)**

Here are the structures of the four most common elements in living organisms.

Atoms are the basis for the chemical world, and each atom is the smallest possible sample of a particular element. Most atoms can react with other elements to form **compounds** and **molecules**.

Atoms are composed of **neutrons**, **protons**, and **electrons**. Neutrons and protons are always in the nucleus and the electrons move rapidly around the nucleus. Elements are defined by the number of protons; all atoms of a particular element have the same number of protons. Protons and neutrons each have a **mass** of approximately one **dalton**; electrons are far less massive.

neutron The neutral particle in the atomic nucleus.

proton The positive particle in the atomic nucleus.

electron The negative particle in an atom, found in orbitals surrounding the nucleus.

mass The amount of "substance" in an object ("weight" is the mass under a particular amount of gravity).

atomic number The number of protons in the nucleus of an atom.

atomic mass The total weight of neutrons and protons of an atom; different isotopes have different atomic masses.

radioactive decay Spontaneous disintegration of a radioactive substance into another element through nuclear division and the release of energy.

ion A charged atom.

Many elements have isotopes, with the same number of protons but a different number of neutrons.

All isotopes of a particular element are chemically identical but have different masses, owing to the change in neutrons. The number of neutrons equals the atomic mass minus the **atomic number**. The **atomic mass** recorded in the periodic table is an average mass for the element.

Adding or subtracting protons from a nucleus creates a new element. New elements form inside stars, nuclear reactors, and nuclear bombs. They also form through **radioactive decay**. When these unstable isotopes break apart, they release energy and form less massive atoms, which may break again into other elements. The emitted energy can be helpful or harmful.

The number of electrons always equals the number of protons in a neutral (uncharged) atom.

Protons have a positive charge and a mass, whereas electrons carry a negative charge but no appreciable mass. The electromagnetic attraction between protons and electrons prevents the electrons from leaving the atom. The positive–negative attraction between proton and electron resembles the north–south attraction between refrigerator magnets and steel refrigerator doors.

What prevents the electrons from slamming into the protons? Magnets, after all, tend to stick to the fridge door. The answer comes from a branch of physics called quantum mechanics, which treats electrons as waves as well as particles. These waves must orbit the nucleus in complete waves; fractional waves are not allowed. An electron wave cannot drop down half a wave—so it stays in a specific orbit, or jumps up or down a full orbit.

Electrons repel each other because they all carry a negative charge. This repulsion is much like what happens when you try to force the north poles of two magnets together. The repulsion, combined with the wave behavior just mentioned, channels electrons into specific energy levels, called **orbitals**, which define the most likely location of electrons at any given moment. Orbitals are best imagined as clouds of electrons surrounding the nucleus.

The outermost energy level of electrons, or **valence shell**, is most important in chemistry and biology, because that is where atoms bond. The Roman numeral above each column in the periodic table indicates the number of valence electrons of all the atoms in that column. That number tells us how the atom will react with other atoms:

- An atom with one to three electrons in its valence shell can lose electrons, forming a positive **ion**. The positive charge results when electrons are lost, because the number of protons does not change.
- An atom with five to seven electrons in its outer shell tends to grab electrons to "fill" the valence shell with eight electrons. These atoms become negative ions able to participate in chemical reactions.
- An atom with eight electrons in the valence shell will usually not bond, because the valence orbital is full. Elements with eight valence electrons include "noble gases" like neon and argon.

Ions and chemical bonds are important within our bodies as discussed in *Health, Wellness, and Disease: Electrolytes and Homeostasis*.

Chemistry encompasses a vast amount of information that can be useful only if it is organized.

A card player knows it's almost impossible to tell which cards are missing from a glance at a shuffled deck. However, if you arrange the cards

HEALTH, WELLNESS, AND DISEASE

NATIONAL GEOGRAPHIC

Electrolytes and Homeostasis

An electrolyte is a substance that, when dissolved, becomes capable of conducting electricity. There are four main electrolytes in the human body: sodium, potassium, chloride, and bicarbonate. Sodium is the major positive ion in the fluid surrounding the cells of the body, while potassium is the major positive ion within body cells. Chloride is the major negative ion in the body fluid, and the bicarbonate ion serves as a buffer to maintain the pH of the blood. An imbalance in any one of these is a serious, often life-threatening problem.

If you do not drink enough water, or lose a large amount of water in a short time due to diarrhea or vomiting, your sodium levels may increase above 135–145 millimoles per liter (mmol/L). Conversely, if you dilute your body fluid by greatly increasing the amount of water you take in, you may suffer from headaches, muscle spasms, weakness, confusion, or seizure brought on by low sodium levels.

The homeostatic range for potassium is 3.5 to 5 mmol/L. Excessive sweating, eating disorders, vomiting, or diarrhea may cause potassium levels to drop below homeostatic range. Increased potassium is usually caused by kidney disorders. Any shift in potassium levels within cells can severely affect the nervous system and heart rate.

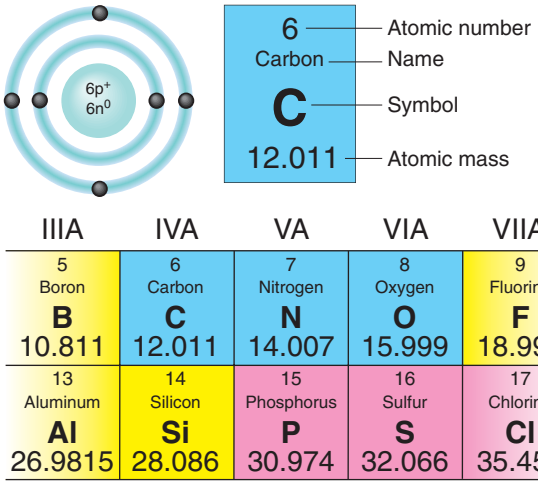
Like potassium, chloride ions increase during kidney disease and decrease with heavy sweating or vomiting. Normally, chloride ion concentration is between 98 and 108 mmol/L. Values outside this range can be fatal.

Bicarbonate levels in the blood should be 22–30 mmol/L. The CO_2 that we breathe out is carried in the bloodstream as bicarbonate. You are probably aware that panting leads to dizziness—this is due to a loss of bicarbonate, which allows a drop in pH of the blood, in turn affecting the brain.

numerically by suit, the pattern reveals which cards are missing. In chemistry, the **periodic table** (see Appendix A at the back of the book for a full version of the periodic table) organizes all elements in a logical pattern, according to atomic number. As you now know, the atomic number is the number of **protons** in the nucleus. The table also reveals an element's reactivity—its ability to bond with other elements, as reflected in the valence electrons. Elements in a particular column have the same number of valence electrons, and thus similar reactive properties. If we are familiar with any element in a column, we can predict the reactivity of other elements in that column.

The periodic table lists each element by a standard one- or two-letter abbreviation, as shown in Figure 3.2. The Internet provides many places to study the periodic table.

Carbon as it appears on the periodic table • Figure 3.2



Chemistry Is a Story of Bonding

Chemistry is a story of bonds made and bonds broken. Bonds between atoms determine how chemical compounds form, fall apart, and re-form. When we metabolize sugar, for example, we are essentially combining its carbon and hydrogen atoms with oxygen, forming carbon dioxide and water. These reactions produce heat and energy that the body uses for just about every purpose. If we don't use sugar and related compounds right away, some of them are converted to fat—larger molecules that store even more energy in their chemical bonds.

Life is made of atoms, but atoms are only the building blocks of molecules and chemical compounds. A molecule is a chemical unit formed from two or more atoms. H_2, for example, is a molecule of hydrogen. A **compound** is a molecule with unlike atoms: CO_2, carbon dioxide, is both a molecule and a compound. The chemical properties of a compound have little or nothing to do with the properties that make up the atoms. Sodium, for example, is a soft metal that burns when exposed to air. Chlorine is a toxic gas at room temperature, but sodium chloride is table salt. The atoms individually are, of course, not alive. Once they combine and become part of us and our environment, however, they become the stuff of life.

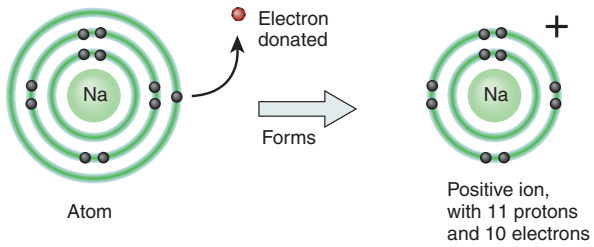
Chemical bonds are a matter of electrons. Atoms without a "filled" valence shell adhere to one another by sharing or moving electrons. Atoms can bond in three common ways, ranging in strength from the strong ionic bonds of salts and the equally strong shared bonds of organic molecules to the weak hydrogen bonds that hold DNA molecules together.

1. The **ionic bond** holds ions in a compound, based on the strong attraction between positive and negative ions—something like the north–south attraction between a refrigerator magnet and refrigerator door discussed previously. The interactions between sodium and chlorine show a typical ionic bond (see **Figure 3.3**).

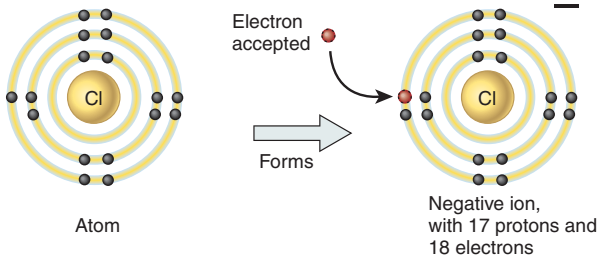
   Many ions in the human body, including calcium (Ca^{2+}), sodium (Na^+), potassium (K^+), hydrogen (H^+), phosphate (PO_4^{3-}), bicarbonate (HCO_3^-), chloride (Cl^-), and hydroxide (OH^-), can form ionic bonds. All these ions play significant roles in homeostasis. In some people, too much sodium can raise blood pressure. Too little calcium causes soft, weak bones as in rickets, and potassium and calcium imbalances can cause heart irregularities. The other ions are vital to maintaining the blood's acid/base balance. If ion levels do not stay within normal range, cellular functions can cease, leading to the death of tissues, organs, and even the organism.
2. Although ions are common in the body, **covalent bonds** are actually more important to living tissue than are ionic bonds. In covalent bonds, atoms share electrons; electrons are not donated by one atom and grabbed by another, as in an ionic bond. Covalent bonds commonly involve carbon, oxygen, nitrogen, or hydrogen, the elements predominant in life. In a covalent bond, atoms share electrons so that each gets to complete its valence shell.

The ionic bond of an NaCl salt molecule • Figure 3.3

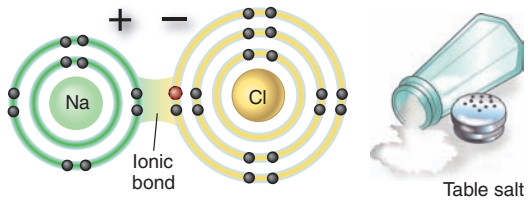
A typical ionic bond: Sodium atoms have one electron in the outer orbital. If this electron is stripped away, the atom becomes a sodium ion (Na^+). Chlorine atoms have seven valence electrons, so they tend to attract free electrons, forming a chloride ion (Cl^-). The attraction between the two ions is an ionic bond.



a. Sodium: 1 valence electron

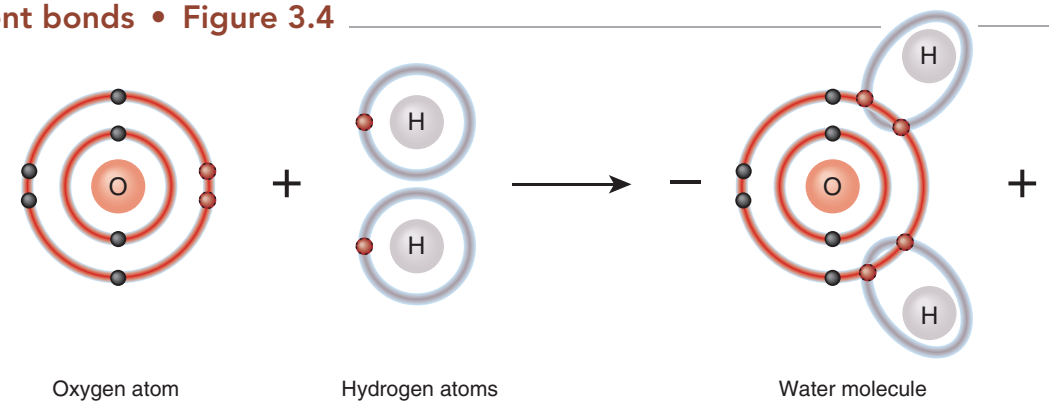


b. Chlorine: 7 valence electrons



c. Ionic bond in sodium chloride (NaCl)

Polar covalent bonds • Figure 3.4



Two atoms share one pair of electrons in a single covalent bond, as occurs in a hydrogen molecule. Single covalent bonds are shown in chemical diagrams as one line: H—H.

In a double covalent bond, two pairs of electrons are shared. For example, two oxygen atoms form an oxygen molecule (O_2) by sharing four electrons. Each oxygen atom has six electrons in its valence shell; with the addition of two more electrons, it gets that stable shell of eight electrons. Double covalent bonds are shown in chemical diagrams with a double line: O═O.

In a triple covalent bond, three pairs of electrons are shared. This is the way that two atoms of nitrogen form a nitrogen molecule (N_2). Nitrogen has five electrons in its valence shell; by sharing six electrons between the two, each can add three electrons, making eight in the valence shell. Triple covalent bonds are shown as a triple line: N≡N.

Carbon has four electrons in the valence shell, so it can complete the valence shell by sharing four electrons. When two carbon atoms form a covalent bond, the electrons are distributed equally between the atoms. Neither atom has a strong enough charge to pull the electrons off the other, but the electromagnetic force of the nuclei does affect the placement of those electrons. Rather than strip electrons from one atom and carry them on the other, the two atoms share the electrons equally. The result is a **nonpolar** molecule (one that is electrically balanced).

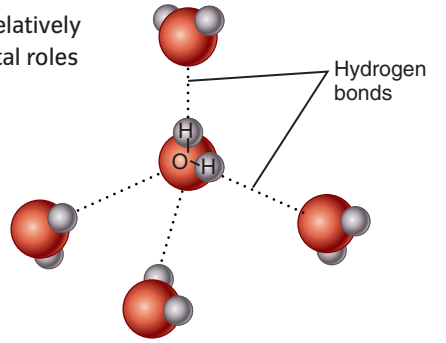
Most covalent bonds in the human body are nonpolar. In some cases, however, one atom has a stronger attraction for the shared electrons (it reminds us of trying to share a cell phone with an older sibling). Unequal electron-sharing on the atomic level creates **polar covalent bonds**, as in Figure 3.4.

In a polar covalent bond, shared electrons reside preferentially near one nucleus, forming a polar molecule. Part of the molecule has a slight negative charge, because the electrons are there more often. The other part of the molecule carries a slight positive charge. Water, a compound that is essential to all forms of life, is a polar molecule; the polar bonds account for many of water's life-giving characteristics.

3. The **hydrogen bond** is weak but vital to biology. When a hydrogen atom is part of a polar covalent bond, the hydrogen end of the molecule tends to be more positive, leaving the other end more negative, as shown in Figure 3.5. The result is a molecule with a charge gradient along its length. The slight positive charge of the hydrogen atom can form weak attractive bonds with adjacent, slightly negative atoms in other compounds. Although the hydrogen bond is too weak to bond atoms in the same way as covalent or ionic bonds, it does cause attractions between nearby molecules. Hydrogen bonds join the two strands of DNA (your genetic material) in the nucleus of your cells. They also help shape proteins, the building blocks of living bodies.

Hydrogen bonds between water molecules • Figure 3.5

Hydrogen bonds are relatively weak, but they play vital roles in biology.

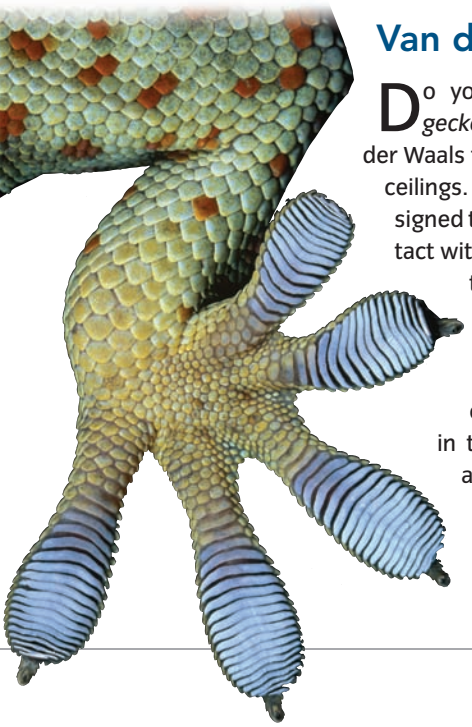


NATIONAL GEOGRAPHIC

WHAT A SCIENTIST SEES

THE PLANNER

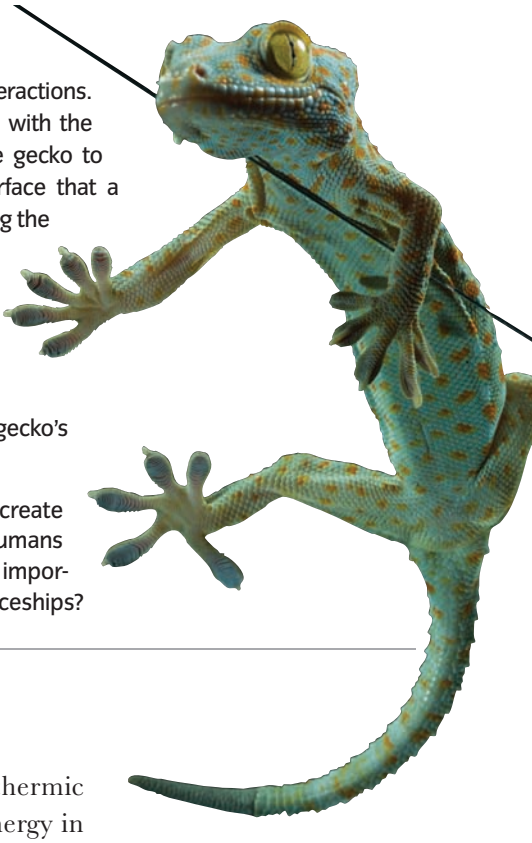
Van der Waals Forces in Nature



Do you recognize the lizard called a *gecko*? We now know that it uses van der Waals forces to walk up walls and across ceilings. The footpads of this lizard are designed to enhance the surface area in contact with the wall. Van der Waals forces literally stick the gecko's foot to the surface it is crawling across.

Recently scientists have discovered that the undersides of the gecko footpads are covered in tiny setae, or hairs. In fact, there are nearly 14,000 of these setae per square millimeter! Additionally, the tips of each of these gecko setae are flared out in a spatula-like structure that provides even more surface area for chemical interactions. Water or other fluids will interfere with the van der Waals forces, causing the gecko to lose its grip. The only known surface that a gecko cannot walk across, assuming the humidity is low enough, is Teflon.

- Knowing that van der Waals forces are weak attractive forces between atoms, how might this force be enhanced by the millions of setae on the gecko's foot pad?
- Can we use this same force to create "moon boots" that will allow humans to walk up walls, and (more importantly) walk in zero gravity spaceships?



Hydrogen bonds occur between water molecules because the electrons of the covalent bond between hydrogen and oxygen preferentially circle the oxygen nucleus. With more negative charges around the oxygen, the result is a partially negative oxygen atom and a partially positive hydrogen atom. The partially negative oxygen in one molecule is attracted to the partially positive hydrogen atoms of another molecule.

A fourth category of atomic interaction, van der Waals forces, has interesting implications for biology. These forces are extremely weak, resulting from intermittent electromagnetic interactions between resonating molecules. As atoms vibrate and electrons whirl in their clouds, various regions briefly become positive or negative. Van der Waals forces occur when these intermittent charges attract adjacent molecules that briefly have opposite charges. Read about one application of van der Waals forces in *What a Scientist Sees: Van der Waals Forces in Nature*.

Bonds do more than hold atoms together in molecules. They also contain energy. Some bonds absorb energy when they form. These **endothermic** reactions include the formation of longer-chain sugars from shorter-chain, simple sugars. Endothermic reactions are used to store energy in the body for later release.

In an **exothermic** reaction, energy is released when the bond is formed. A common exothermic reaction is simple combustion:

$$C + O_2 = CO_2$$

A second is the burning of hydrogen:

$$2\,H_2 + O_2 = 2\,H_2O$$

CONCEPT CHECK

STOP

1. **What** are the four most common chemicals in living organisms?
2. **What** influence does an atom's number of valence electrons have on its reactivity?
3. **What** is the difference between a polar and a nonpolar molecule?
4. **How** is atomic number determined, and **why** is it different from atomic mass?
5. **What** are the three types of chemical bonds and **how** do they compare to each other in terms of strength?

3.2 Water Is Life's Essential Chemical

LEARNING OBJECTIVES

1. **Define** the six properties of water that are critical to life.
2. **Develop** an understanding of the pH scale.
3. **Identify** the biological significance of acids, bases, and buffers.

We all know water. We drink water; swim in it; surf, ski, and float on it; use it to maintain our lawns and plants; and even cool our vehicles and heat some of our homes with it. It is the most abundant molecule in living organisms, making up between 60 and 70% of total body weight. Our bodies need water to carry out the basic functions of digestion, excretion, respiration, and circulation. Without adequate water, the body's chemical reactions would fail and our cells would cease to function—we would die. Interestingly, scientists have often noted that we cry and sweat seawater—meaning that the percentages of salts and minerals in our tears and perspiration are similar to those found in seawater. As we know, we are products of our environment and can identify examples of our interdependence with the environment. Crying seawater is one of many such examples.

Six Properties of Water Are Critical to Life

1. Water is liquid at room temperature, whereas most compounds with similar molecular weights are gases. At sea level, water becomes a gas (vaporizes) only at or above 100°C. Water remains liquid due to the hydrogen-bond attraction between molecules.
2. Water is able to dissolve many other substances and, therefore, is a good solvent. The two atoms of hydrogen and one of oxygen have polar covalent bonds, making the molecule polar. This polar characteristic sets up a lattice of water molecules in solution. As water molecules move, the hydrogen bonds between them continually form and break. Substances that are surrounded by water are subjected to constant electromagnetic pulls, which separate charged particles—causing the compound to break down, or dissolve. Polar covalent molecules align so that negative ends and positive ends sit on the respective complementary areas of the solute and pull it apart. **Hydrophilic** substances, such as NaCl (salt), carry a charge and are immediately separated in water. **Hydrophobic** substances are not soluble in water. Hydrophobic substances include large, uncharged particles like fats and oils. In the human body, fats and oils separate cells from the surrounding fluids of the body. Even though water cannot dissolve hydrophobic compounds, it is still called the "universal solvent."

hydrophilic Having an affinity for water.

hydrophobic Lacking an affinity for water.

cohesive Having the ability to stick to itself.

adhesive Having the ability to stick to other surfaces.

3. Water is both **cohesive** and **adhesive**, allowing it to fill vessels and spaces within the body. This property also allows water to line membranes and provide lubrication. Your blood plasma is 92% water, which allows it to stick to the sides of the vessels and fill them completely.
4. Water has a high **specific heat**—it takes a lot of energy to raise or lower its temperature. It takes one **calorie** of energy to raise the temperature of one gram of water one degree Celsius. (A different calorie is used in dieting: It is actually a kilocalorie: 1 kcal = 1,000 calories.) Water therefore serves as a temperature buffer in living systems. Water does the same for the Earth. Look at a weather map and compare the temperature ranges for coastal and inland areas. The temperature range is much smaller near the coast than it is inland. The highest and lowest temperatures ever recorded both come from inland areas. Vostok, Antarctica, located in the center of that continent, hit an amazingly frigid −89°C in 1983.
5. Water has a high **heat of vaporization**, a measure of the amount of heat needed to vaporize the liquid. A large amount of heat energy, 540 calories, is needed to convert 1 g of water to vapor. This is important for thermal homeostasis. Your body cannot survive unless it remains in a narrow temperature range, and a great deal of excess heat is generated by cellular activity. Much of this heat is lost through the evaporation of water from your

skin. As your core temperature rises, your body responds by increasing sweat production to increase evaporative heat loss. (A second homeostatic regulation to maintain the all-important temperature is increase in blood flow, which transfers heat from the core to the skin.)

6. **Ice floats**. As water cools, the molecules lose energy and move more slowly. The hydrogen bonds that continuously break and re-form in the liquid cease to break, and the water turns solid. The bonds hold a specific distance between the molecules, making solid water slightly less dense than liquid water. Freezing a can of soda shows what happens: As the water inside freezes, the can deforms and may even rip open. Frostbite can occur if tissues freeze. The water within and between the cells expands, bursting and crushing the cells. The tissue dies because its cellular integrity is lost. On the positive side, ice that forms on lakes stays at the surface, allowing fish to survive in the cold (but liquid) water near the bottom.

Hydrogen and Hydroxide Ion Concentration Affects Chemical Properties

One of the most important ions is hydrogen, H^+, which is simply a bare proton. In pure water, some of the molecules dissociate, releasing equal numbers of H^+ and hydroxide ions (OH^-). Pure water is neutral. If the concentration of H^+ increases, the solution becomes acidic; if the OH^- concentration increases, it becomes basic, or alkaline.

Acidity matters to the human body because it affects the rate of most chemical reactions and the concentration of many chemicals. As we'll see shortly, the body has various mechanisms for maintaining proper acidity, through the use of buffer systems.

Lemon juice, orange juice, cranberry juice, vinegar, and coffee are common acids. They taste "sharp" and can cause mouth sores or indigestion if consumed in large quantities. The bite in carbonated beverages results from the formation of carbonic acid in the drink. When these beverages go "flat," the acid content is reduced because the carbonic acid has been converted to carbon dioxide, which leaves the solution as carbonation bubbles.

The pH scale measures the concentration of H^+ and OH^- and ranges from 0 to 14. Lower pH readings indicate a higher H^+ concentration and greater acidity. A higher pH reading indicates higher OH^- concentrations and greater alkalinity. A pH indicator is used to measure a solution's acidity or alkalinity, as shown in Figure 3.6. One of the first pH indicators was litmus, a vegetable dye that changes color in the presence of acid or base. Litmus turns from blue to red in the presence of ac-

pH • Figure 3.6

a. Testing the pH of a solution—the pH scale is logarithmic: A change of 1 means a 10 × change in H^+ concentration.

b. Acidic and basic scale of common substances.

ids, and from red to blue with bases. This test is simple and so definitive that it has become part of our language. For example, in extreme-sport circles you might hear, "That jump is the litmus test for fearless motocross riders."

Pure water registers 7 on the pH scale, meaning it has equal numbers of H^+ and OH^- ions. In pure water, 10^{-7} **moles** of molecules dissociate per liter (1 mole = 6.023×10^{23} atoms, molecules, or particles). Note that the pH scale is logarithmic: Each one unit represents a tenfold change in H^+ concentration. Thus a change from pH 3 to pH 8 would reduce the H^+ concentration by a factor of 100,000.

Strong acids dissociate (break apart) almost completely in water, adding a great deal of H^+ to the solution. Weak acids dissociate poorly, adding fewer H^+. Hydrochloric acid, one of the strongest acids used in the laboratory and also found in your stomach, is pH 2. Concentrated hydrochloric acid can injure the skin in minutes or dissolve a steel nail in a few days, which is a bit frightening when you realize soft drinks are very nearly one pH unit (not quite 10 times) less corrosive! If any material is strongly acidic or basic, it should carry a warning label like the one in **Figure 3.7**.

A basic solution has more OH^- ions than H^+ ions and a pH of 7.01 to 14. Like acids, bases are classified as strong or weak, depending on the concentration of OH^-. Like strong acids, strong bases are harmful to living organisms because they destroy cell structure. Common bases include soaps, such as lye, milk of magnesia, and ammonia. Basic solutions generally taste bitter and feel slippery, a feeling you may have noticed the last time you cleaned with ammonia.

Acids and bases cannot coexist. If both H^+ and OH^- are present, they tend to neutralize each other. When a base dissociates in water, it releases hydroxide ions into the solution. However, if a base dissociates in an acidic solution, its OH^- ions bond to H^+ ions, forming water, which tends to neutralize the solution.

Your body cannot withstand a shift in acidity any better than it can a shift in temperature. The pH of your blood must stay between 7.4 and 7.5 for your cells to function. Because pH is critical to biological systems, various homeostatic mechanisms exist to keep it in the safe range. One mechanism utilizes biological **buffers**, compounds that stabilize pH by absorbing excess H^+ or OH^- ions.

One of the most common buffering systems for blood pH consists of carbonic acid, H_2CO_3, and bicarbonate ion, HCO_3^-. In water, carbonic acid dissociates into H^+ and HCO_3^-. The H^+ can bond to OH^-, forming water, whereas the bicarbonate ion can bond to a hydrogen ion, re-forming carbonic acid. The carbonic acid–bicarbonate system works in either direction. When excess H^+ is present (the system is acidic), bicarbonate and hydrogen ion combine, forming carbonic acid:

$$HCO_3^- + H^+ \rightarrow H_2CO_3$$

When hydrogen ion levels are too low, carbonic acid becomes a source of hydrogen ion:

$$HCO_3^- + H^+ \leftarrow H_2CO_3$$

Chemists write this as a reversible reaction, with a double-ended arrow in the middle to indicate that it can go in either direction, depending on conditions around the reaction:

$$HCO_3^- + H^+ \rightleftharpoons H_2CO_3$$

A similar buffering system is used in some common anti-acid medicines. Many contain calcium carbonate, $CaCO_3$, which dissociates into calcium ion, Ca^{2+}, and carbonate ion, CO_3^{2-}.

Hazardous material • Figure 3.7

When a household cleanser has a strong acid or base content, such as a pH of 3 or 10, it should carry a warning like this.

CONCEPT CHECK STOP

1. **What** are the six properties of water that are critical to life?
2. **What** acid/base terms would you use to describe milk, which has a pH of 7.6? Homemade soap, which has a pH of 10?
3. **What** is the biological significance of a buffer?

3.3 There Are Four Main Categories of Organic Chemicals

LEARNING OBJECTIVES

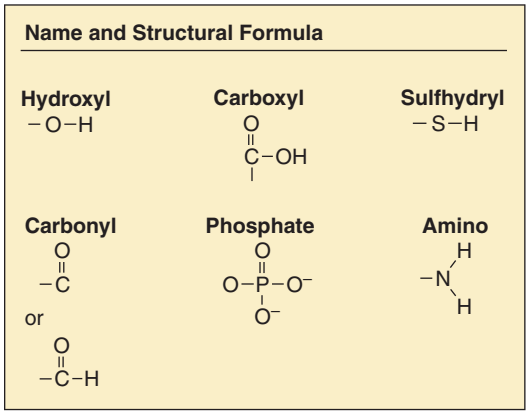
1. **Identify** the main categories of organic compounds.
2. **Define** the roles of carbohydrates, lipids, proteins, and nucleic acids in the human body.
3. **Explain** the function of ATP in energy storage and usage.

When we discuss life, we are discussing organic chemistry. Scientists used to think that all organic chemicals were made by organisms. Although that's not true, organic chemicals are usually made by organisms, and they always contain carbon. In terms of bonding, carbon is astonishingly flexible. With four valence electrons, it can bond covalently with four other atoms, leading to an almost infinite set of carbon structures, from simple methane, CH_4, to highly complex rings and chains. In organic compounds, carbon often bonds with two carbons and two hydrogens. The resulting hydrocarbon compounds can be chain or ring structures. Attached to the carbon/hydrogen core are **functional groups** that determine the compound's reactivity (see Figure 3.8).

functional group
Subunit on an organic molecule that helps determine how it reacts with other chemicals.

Organic compounds are grouped into four main categories: **carbohydrates**, **lipids**, **proteins**, and **nucleic acids**.

Functional groups • Figure 3.8



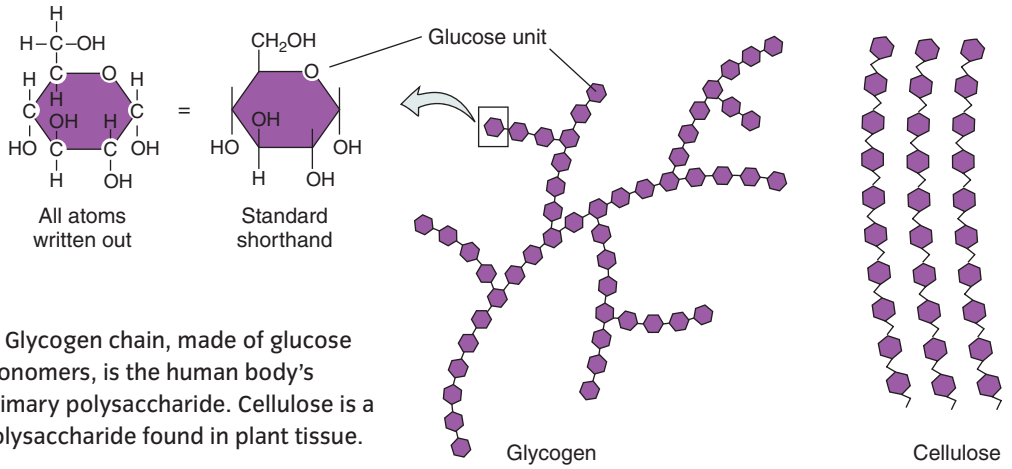
These functional groups are found on a variety of organic molecules. Each group is usually found attached to a long string of carbon molecules.

Carbohydrates Are the Best Energy Source for the Human Body

Carbohydrates are organic molecules that are quite abundant in organisms. A carbohydrate is composed of carbon, hydrogen, and oxygen in a ratio of 1:2:1. Many carbohydrates are **saccharides** (sugars). Glucose, as shown in Figure 3.9,

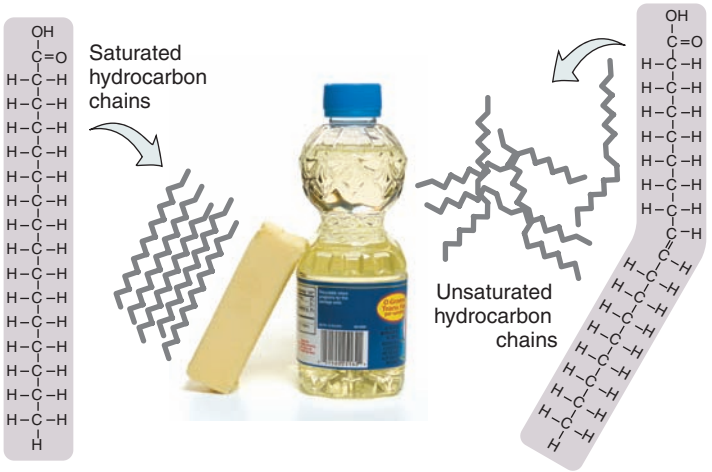
Glucose, glycogen, and cellulose • Figure 3.9

a. The glucose molecule, $C_6H_{12}O_6$, can be diagrammed in two ways.



b. Glycogen chain, made of glucose monomers, is the human body's primary polysaccharide. Cellulose is a polysaccharide found in plant tissue.

Saturated and unsaturated fats • Figure 3.10



Saturated fats usually have animal origins. At room temperature, these fats are composed of tightly packed, straight lipid molecules. Unsaturated fats are usually plant products and have kinked lipid molecules that will not pack together tightly at room temperature.

and fructose are both simple sugars. They are called **monosaccharides** because they have one ring of 6 carbons, with 12 hydrogens and 6 oxygens attached. **Oligosaccharides** and **polysaccharides** are longer sugar chains (*oligo* = few, and *poly* = many). **Disaccharides**, such as sucrose and lactose, are common in the human diet. **Glycogen,** also in Figure 3.9, is a polysaccharide sugar molecule stored in animal tissue. It is a long chain of glucose molecules, with a typical branching pattern. Glycogen is stored in muscles and the liver, where it is readily broken down when needed.

Unlike glycogen, **starch** is a fairly long, straight chain of sugars. Plants store energy in starch, often in roots, tubers, and grains. **Cellulose**, another polysaccharide, has a binding pattern similar to glycogen. Cellulose is often used in structural fibers in plants and is the main component of paper. The difference between cellulose and glycogen depends on which particular carbon on the sugar ring connects the branches to the main chain. This small difference makes cellulose indigestible to humans, whereas glycogen is an easily digestible source of quick energy.

Despite the hoopla surrounding the high-protein Atkins diet, carbohydrates are the best energy source for the human body: We are efficient carbohydrate-burning machines. Restricting intake of carbohydrates and increasing intake of other organic compounds puts biochemical stress on the whole body. When digesting proteins, for example, we generate nitrogenous wastes, which can release potentially harmful nitrogen compounds into our blood.

Water is needed to digest carbohydrates. In the process of **hydrolysis**, digestive enzymes insert a water molecule between adjacent monosaccharides in the chain, disrupting the covalent bond between sugars and releasing one sugar molecule. To add a sugar molecule to a chain, the opposite of hydrolysis must occur. In **dehydration synthesis**, a molecule of water is removed from adjacent glucose molecules, allowing them to bond. By adding water, digestive enzymes separate glucose molecules from glycogen and starch. Once glucose enters a cell, it can be completely metabolized into carbon dioxide and water, producing energy through the process of cellular respiration described in Chapter 15. Because we lack the enzymes needed to remove sugar molecules from cellulose, all the cellulose we eat travels through our digestive system intact. This "fiber" is not converted into fuel, but it is essential for proper digestion and defecation.

Lipids Are Long Chains of Carbons

Lipids, such as oils, waxes, and fats, are long-chain organic compounds that are not soluble in water. Although most of the human body is aqueous, it is divided into cells, as described in Chapter 4. Because water does not dissolve lipids, they form a perfect barrier between these aqueous compartments. Lipids, like other organic compounds, are composed of carbon, hydrogen, and oxygen, but NOT with the 1:2:1 ratio of carbohydrates. The carbon–hydrogen ratio is often 1:2, but lipids have far fewer oxygens than do carbohydrates. Lipids have a high energy content (9 kcal/g), and most people enjoy the "richness" they impart to food.

Humans store excess caloric intake as fats, so reducing lipids is a common dietary tactic. As the proportion of stored lipids in the body rises, people become overweight or obese, as discussed in Chapter 14.

Fatty acids are energy-storing lipids. A fatty acid is a long chain of hydrogens and carbon, sometimes with more than 36 carbons. A carboxyl (acid) group is attached to the end carbon, which gives it the name "fatty acid." The other carbons are almost exclusively bonded to carbons or hydrogens. These chains are hydrophobic; the carboxyl group is the only hydrophilic location. Generally, the longer the hydrocarbon chain, the less water soluble the fatty acid will be.

You have no doubt heard about two types of fatty acid: **saturated** and **unsaturated** fats (**Figure 3.10**). Saturated fats have no double bonds between carbons in the fat chains. For this reason, they are completely *saturated* with hydrogens and cannot hold any more. The straight chains of hydrocarbons in a saturated fat allow the individual

chains to pack close together. Saturated fats, such as butter and other animal fats, are solid at room temperature. Unsaturated fats have at least one double bond between adjacent carbons. This puts a crimp in the straight carbon chain, preventing close packing of the molecules. As a result, unsaturated fats are liquid at room temperature. Examples of unsaturated fats include vegetable oils and the synthetic fats added to butter substitutes. Some vegetable oils are "hydrogenated" to remain solid at room temperature. Hydrogenating adds hydrogens, removes double bonds, and straightens the molecular arrangement of the fats. This process allows the lipid to act like an animal fat and to be solid or semisolid at room temperature.

A **triglyceride** is three fatty acids attached to a glycerol backbone. Triglycerides, the most abundant fat in the body, can store two to three times as much energy per gram as carbohydrates. The body manufactures triglycerides as nonpolar, uncharged storage molecules. In adipose (fat) tissue, excess calories are stored in droplets of triglycerides.

Eicosanoids are essential lipids that serve as raw materials for **prostaglandins**. Prostaglandins are short-chain fatty acids that regulate local signaling processes. When nearby cells detect prostaglandins, they respond immediately with the sensation of pain. Aspirin blocks prostaglandins from reaching their cellular target, whereas ibuprofen competes for the site where prostaglandins bind to cells. Ibuprofen acts more like the game of musical chairs, with the pain receptor as the chair and prostaglandin as the other player. Because aspirin blocks prostaglandins entirely, it is more effective against some pain.

Phospholipids are another key group of lipids. As shown in **Figure 3.11**, phospholipids are fats that have two fatty acids and one phosphate group attached to a glycerol backbone. The fatty acids comprise the hydrophobic tail, whereas the phosphate group serves as a hydrophilic head. This unique structure allows phospholipids to form double layers (bilayers) that attract water on their edges and yet repel water from their center. The cell membrane, explored in the next chapter, is one such bilayer.

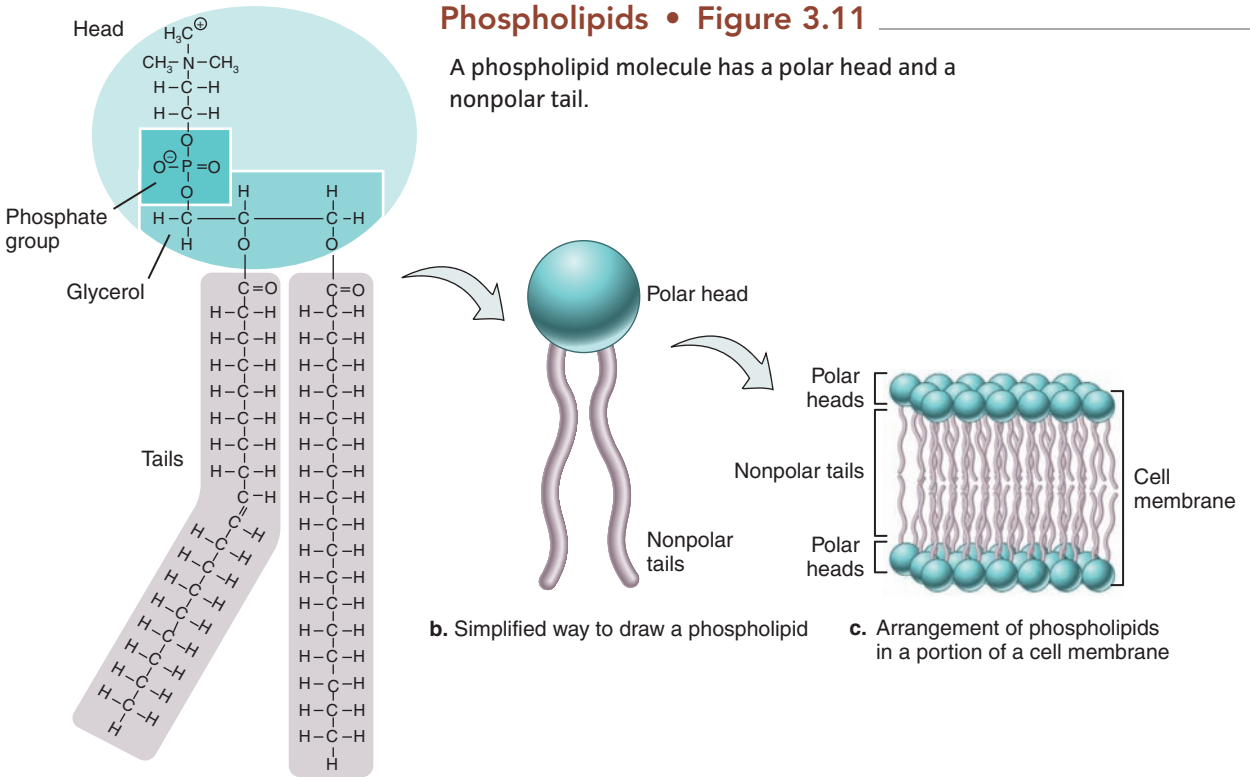
Steroids are a final group of lipids that often makes news. These are large molecules with a common four-ring structure, important to normal growth and development. Steroids include cholesterol, sex hormones, and metabolism regulators, as shown in **Figure 3.12**.

Cholesterol is an integral part of cell membranes that allows for

cholesterol A class of steroids found in animals; aids in membrane fluidity.

Phospholipids • Figure 3.11

A phospholipid molecule has a polar head and a nonpolar tail.



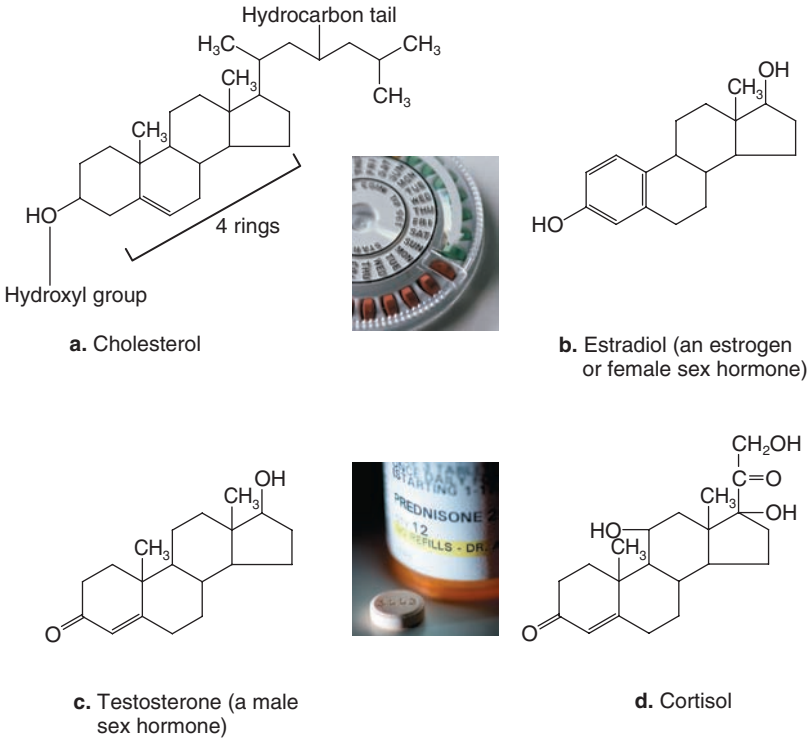
a. Chemical structure of a phospholipid

b. Simplified way to draw a phospholipid

c. Arrangement of phospholipids in a portion of a cell membrane

Steroids • Figure 3.12

The body synthesizes cholesterol into other steroids, which play essential regulatory roles as hormones. Regulatory hormones, such as cortisone, maintain salt and calcium balance in the fluids of the body.



a. Cholesterol

b. Estradiol (an estrogen or female sex hormone)

c. Testosterone (a male sex hormone)

d. Cortisol

flexibility and growth. High blood cholesterol has been linked to heart disease, so dietary restriction of cholesterol is often suggested. However, because your body synthesizes cholesterol, it is often difficult or even impossible to manage cholesterol levels solely by diet.

The sex hormones **estrogen** and **testosterone** are two steroids that are responsible for the enormous changes of puberty. Anabolic steroids, which are related to testosterone, stimulate growth of the muscles. Anabolic steroids have important medical value as replacement hormones for males and females with low levels of testosterone or human growth hormone. Although many athletes have taken anabolic steroids to increase muscle mass and improve performance, these substances are banned in most sports.

The health concerns of environmental estrogens are discussed in *Ethics and Issues: Environmental Estrogens: Are We Feminizing the Planet?* on page 58.

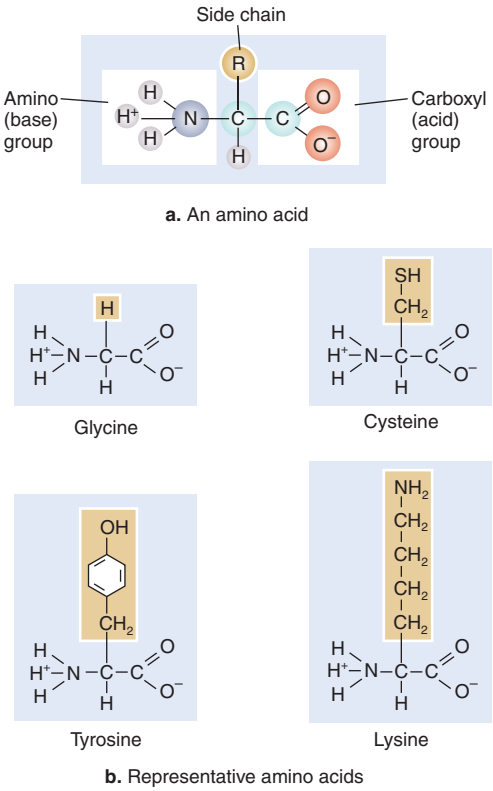
Proteins Are Both Structural and Functional

Proteins contain carbon, hydrogen, oxygen, and nitrogen and are the most abundant organic compounds in your body. You contain more than 2 million different proteins. Some provide structural support, and others function in physiological processes. Proteins provide a framework for organizing cells and a mechanism for moving muscles. They are responsible for transporting substances in the blood, strengthening tissues, regulating metabolism and nervous communications, and even fighting disease.

Millions of different proteins are all formed from just 20 amino acids. An amino acid is composed of a central carbon atom with four groups attached to it: (1) a hydrogen atom, (2) an amino group (—NH_2), (3) a carboxyl group (—COOH), and (4) a radical group or side chain (R). The R group determines the activity of the amino acid, as shown in **Figure 3.13**.

Amino acid structure • Figure 3.13

Amino acids are the building blocks of proteins. Twenty amino acids combine to form millions of proteins. Note that the only difference between these amino acids is the composition of the "R" side chain. Each amino acid has a different side chain, and each side chain has different reactive properties.



a. An amino acid

b. Representative amino acids

WILEY PLUS Video

ETHICS AND ISSUES

THE PLANNER

Environmental Estrogens: Are We Feminizing the Planet?

Estrogens are female sex hormones, present in both males and females. Together with male steroid hormones, they help control the development of numerous body systems and are responsible for sexual maturation and reproduction. However, if they are present in overly high concentrations in either females or males, estrogens have been shown to cause birth defects in offspring, abnormal sexual development, immune and organ system problems, and some forms of cancer.

Because most people's bodies produce estrogens in the proper amount, the question arises: Where is the estrogen overload in some people coming from? The answer is that environmental estrogens are all around us. Some are naturally occurring, while others are present in commonly used chemicals or byproducts of industrial processes.

Phytoestrogens, which are naturally occurring, are found in fruits, vegetables, grains, legumes, and seeds. Estrogens are also associated with heavy metals, such as lead, mercury, and cadmium. There are estrogens in products as diverse as pesticides and fungicides, plastics, ordinary household cleaners and solvents, and pharmaceuticals.

These products may add enough estrogens to the environment to cause birth defects and reproductive failures in many animal species. For example, the Florida panther population suffers from sterility, thought to be caused by high levels of environmental estrogen in their prey.

Human beings, along with other animals, have been exposed to phytoestrogens for thousands of years, but only in the last 100 years or so have chemical estrogens been released into the environment through product development and manufacturing processes. It is tempting to say that because much environmental estrogen is either naturally occurring or the byproduct of products and processes that are important to human health and well-being, it is impossible to avoid and therefore not worth worrying about. From a critical perspective, however, the issue of environmental estrogen warrants closer examination.

Critical Reasoning Issues A critical reasoner develops the habit of doing a risk-benefit analysis on issues like this. The key to such an analysis is knowing as much as possible about both the risks and the benefits. What if limiting human exposure to environmental estrogen may cause more harm than would be caused by allowing such exposure to occur? Consider an example: A commonly used estrogen-carrying drug is cimetidine, which is used to treat acid reflux disease. Do the risks associated with exposure to residual estrogen override the benefits of using cimetidine for patients with acid reflux disease?

Think Critically

1. Plastics also contain estrogens. Should plastics therefore be banned or drastically limited? After all, when properly recycled into sturdy replacements for picnic tables, park benches, and footbridges on walking paths, plastics greatly reduce the need for pressure-treated lumber, which uses chemicals that may indeed be more dangerous than environmental estrogens.
2. Another way of looking at the problem is to consider whether a better solution might be for individuals to limit their own exposure to environmental estrogens through the choices they make about products they use. Would such a solution be effective, or should we seek broad-based public-policy solutions?

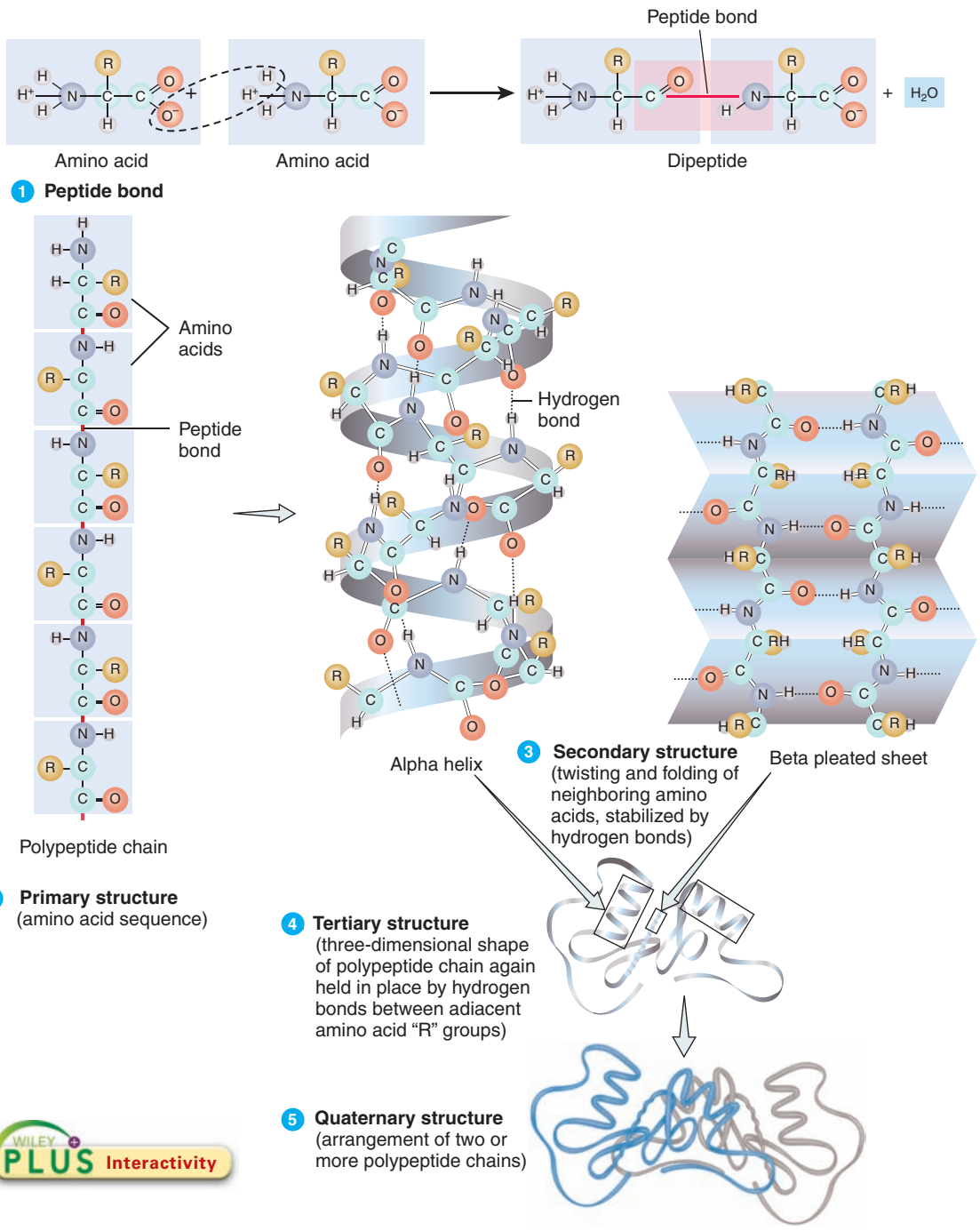
Individual amino acids combine to form proteins, using **peptide bonds** that form between the amino group of one amino acid and the carboxyl group of the next. The resulting two-amino-acid compound is called a dipeptide.

peptide bond
Covalent bond between the carboxyl group of one amino acid and the amino group of the adjacent amino acid.

As more amino acids join the growing chain, it becomes a **polypeptide**. As a rule of thumb, when the amino acid count exceeds 100, the compound is called a protein. **Figure 3.14** shows the formation of proteins from amino acids.

THE PLANNER

The making of a protein • Figure 3.14



WILEY PLUS Interactivity

Insulin, the hormone that stimulates the cellular uptake of glucose, was the first polypeptide whose sequence of amino acids was determined. Frederick Sanger and his coworkers determined the sequence in 1955, and Sanger earned the first of two Nobel Prizes for chemistry in 1958. (His second Nobel was awarded in 1980 for his work in determining the nucleotide sequence of a virus that attacks bacteria.) Insulin is a short polypeptide, with only 51 amino acids. Titin, the largest protein isolated so far from humans, is found in muscles and contains over 38,000 amino acids.

The folding and interacting of adjacent amino acids determine the shape of a protein. The folding brings different amino acids together. If they repel one another, the protein bends outward. If they attract via weak hydrogen bonds, they bend inward, as shown in Figure 3.14.

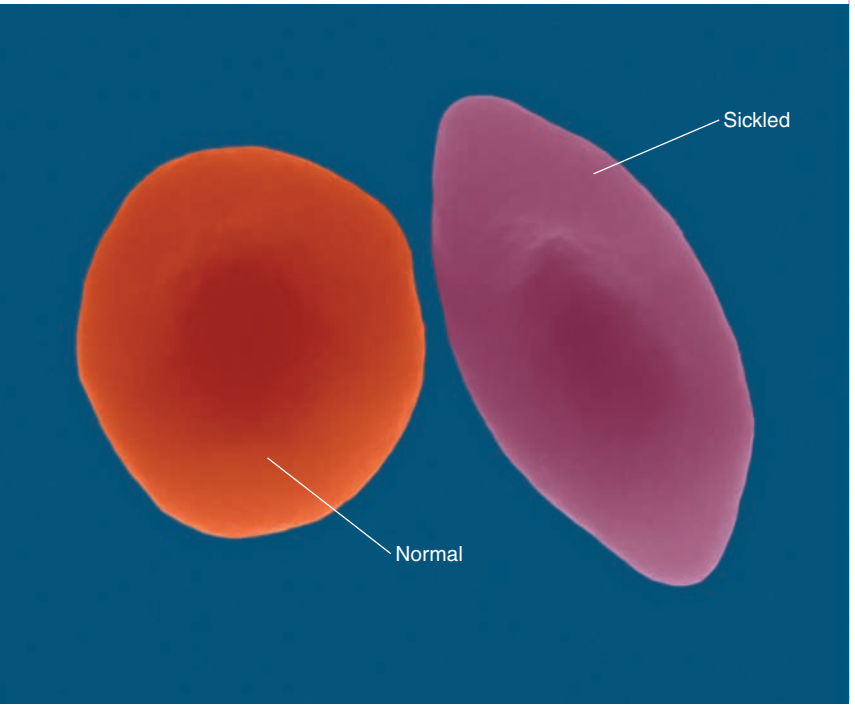
Proteins have four levels of structural complexity. Their **primary structure** is the unique order of amino acids in the chain. Nearby amino acids interact via hydrogen bonds to form either alpha helixes or beta, pleated sheets, which is the **secondary structure**. The **tertiary structure** emerges from interactions between adjacent amino acids of the helical or pleated sheets, creating a complex coiling and folding. Tertiary structure is a result of the hydrophobic and hydrophilic portions of the molecule twisting to either associate with water or to "hide" from it inside the molecule. The **quaternary structure** emerges from the looping of two or more strands around one another. Some proteins have only one strand, but many, including hemoglobin, are composed of two or more polypeptide chains.

The final shape of a protein is either **globular** or **fibrous**. Globular proteins are round and usually water-soluble. These are often functional proteins, such as enzymes and contractile proteins. Fibrous proteins are stringy, tough, and usually insoluble. They provide the framework for supporting cells and tissues.

The shape of a protein molecule determines its function, and the final shape is determined by its primary structure. Changing even one amino acid can alter the folding pattern, with devastating effects on the protein's function, as shown in Figure 3.15.

In sickle cell anemia, a change of one amino acid from the normal hemoglobin protein creates a protein that fails to deliver oxygen correctly. When normal hemoglobin releases its oxygen to a tissue, the protein remains globular. A "sickled" hemoglobin molecule becomes sharp, deforming the entire red blood cell into the sickle shape. These cells can get lodged in small blood vessels, causing pain and interfering with oxygen flow to the tissues.

Microscan of normal and sickled red blood cells (sickle cell anemia) • Figure 3.15



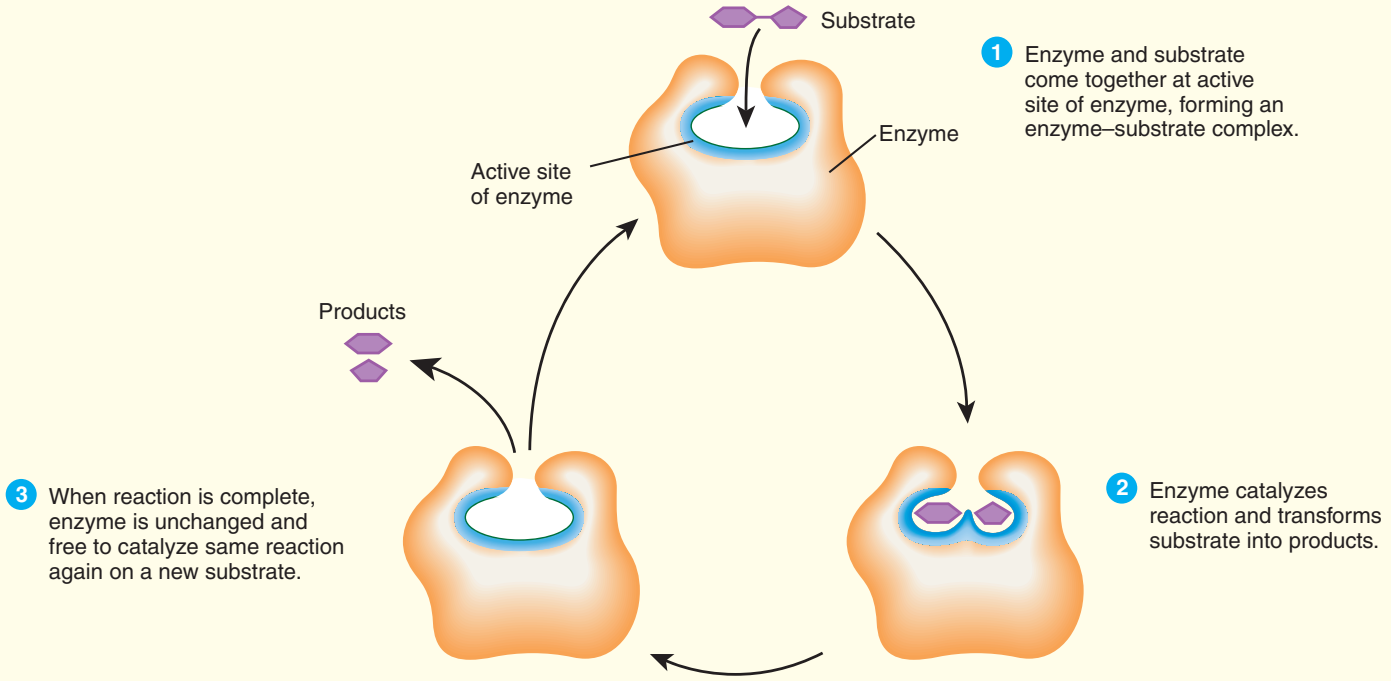
Proteins and their bonds are susceptible to minor changes in the environment, such as increased temperature or decreased pH. When a protein unfolds, or radically alters its folding pattern in response to environmental changes, we say it is **denatured**. This happens when we cook. As we heat eggs, proteins in the clear whites unfold, forming a cloudy mass. This reaction is not reversible; denaturing is often permanent.

Enzymes are a special class of functional proteins. Enzymes serve as **catalysts** for biochemical reactions—meaning that they facilitate a specific reaction without being altered during it. Catalysts bring the reactants, or substrates, together, so a reaction can occur much more quickly. Enzymes rely on shape to function properly. The **active site** of the protein is shaped to bind to one specific substrate. After the substrate binds, the enzyme provides an environment for the specific chemical reaction to occur. See Figure 3.16. Most enzymes are proteins, although some reactions are catalyzed by RNA, a form of nucleic acid.

Most Nucleic Acids Are Information Molecules

The fourth and final class of organic compounds is the **nucleic acid**. These are large molecules composed of carbon, hydrogen, oxygen, nitrogen, and phosphorus. Nucleic acids store and process an organism's hereditary information.

Enzyme activity • Figure 3.16



The two types of nucleic acid are **deoxyribonucleic acid (DNA)** and **ribonucleic acid (RNA)**.

DNA exists in the nucleus of our cells. It contains the hereditary (genetic) information of the cell. DNA encodes the information needed to build proteins, to regulate physiological processes, and to maintain homeostasis. The genes that make each individual and each organism unique are carried as codes in the DNA; see Figure 3.17 on the next page.

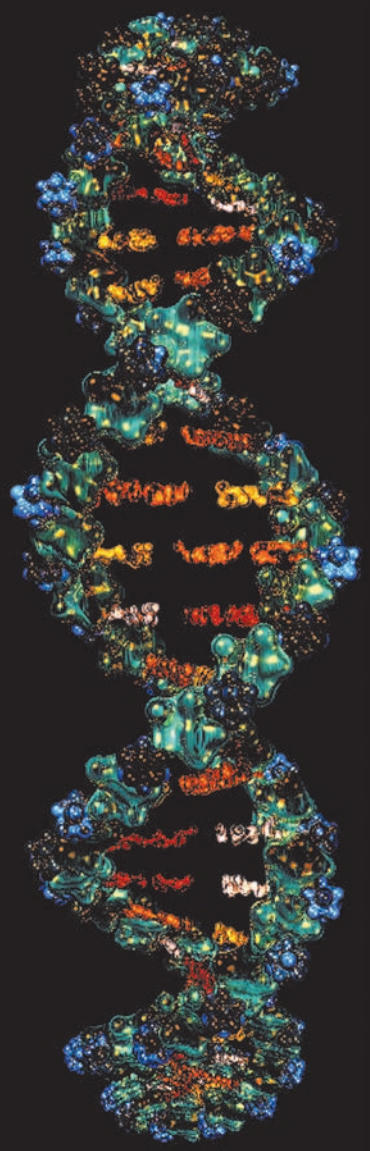
The sugar in DNA is a deoxyribose, meaning it lacks an oxygen, whereas RNA contains a simple ribose sugar. DNA has four bases: adenine (A), thymine (T), cytosine (C), and guanine (G). RNA also has these four bases, with one change: in RNA, uracil (U) appears instead of thymine. DNA is a double-stranded molecule. To fit the two DNA strands of one macromolecule together neatly and precisely, the strands lie antiparallel to one another—meaning that although they lie parallel, they run in opposite directions. The phosphate end of one strand opposes the hydroxyl end of the other. James Watson and Francis Crick, who discovered DNA's structure, could not make their model mathematically fit without the antiparallel configuration. The antiparallel arrangement of DNA strands is paramount to the entire molecule—one strand must be upside down in relation to the other.

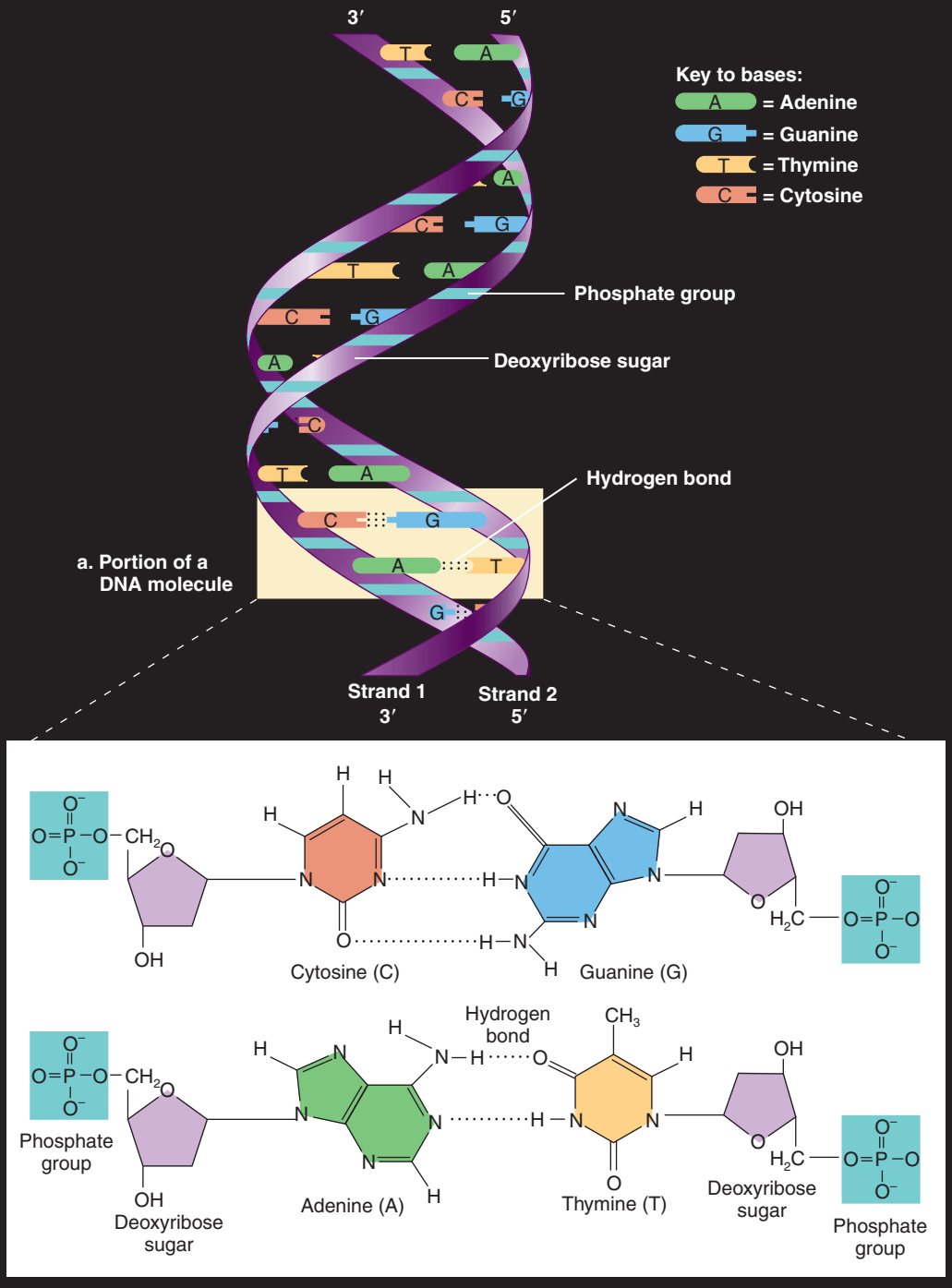
During DNA replication, this antiparallel configuration provides a logical explanation for why one strand is replicated with ease, whereas the other one is copied in "fits and starts." The enzyme responsible for duplicating the DNA can read in only one direction. It replicates DNA just as you read easily from left to right. The enzyme cannot read in the opposite direction, slowing the replication process. Imagine how much more slowly you would read these words if they made sense only from right to left.

The two chains of DNA nucleotides wrap around one another in a doubled **alpha helix**, held together by hydrogen bonds between bases. In naturally occurring DNA, the ratio of adenine to thymine is usually 1:1 and the ratio of cytosine to guanine is again approximately 1:1. These ratios indicate that A bonds to T and C to G. Every time you find an adenine base on one strand of DNA, you will most likely see it base-paired to a thymine on the complementary strand.

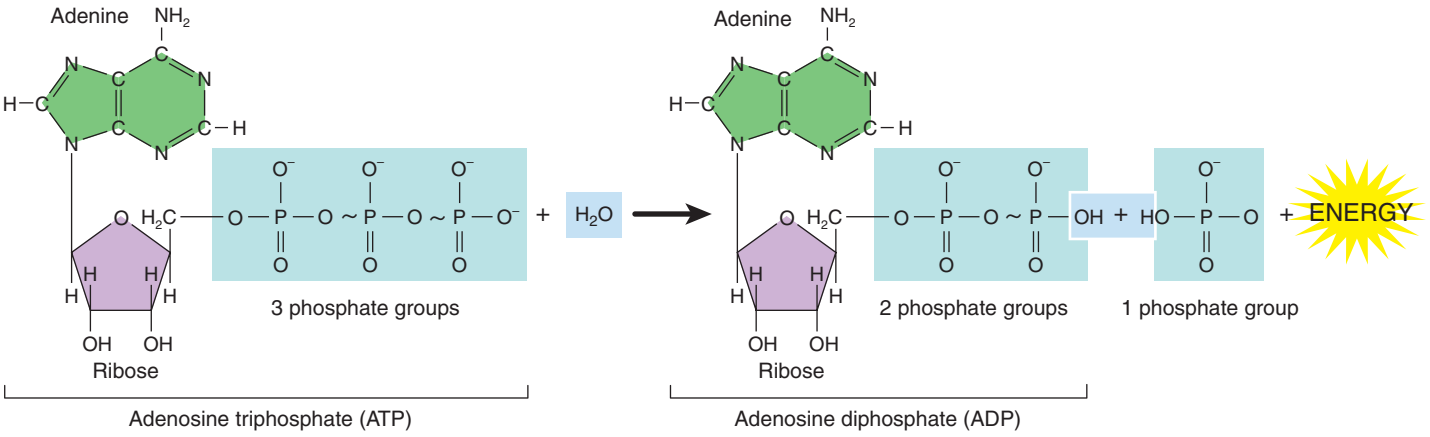
alpha helix Spiral chain of monomers, resembling an old-fashioned telephone cord.

A nucleotide consists of a base, a pentose sugar, and a phosphate group. The paired bases of DNA project toward the center of the double helix. The structure is stabilized by hydrogen bonds (dotted lines) between each base pair. There are two hydrogen bonds between adenine and thymine and three between cytosine and guanine.





Adenosine triphosphate (ATP) and adenosine diphosphate (ADP) • Figure 3.18



Adenosine triphosphate (ATP) + H_2O = Adenosine diphosphate (ADP) + P_i + Energy

RNA is not a storage unit, and it may occur inside or outside the nucleus. RNA serves to regulate cellular metabolism, produce proteins, and govern developmental timing. RNA is usually a single-stranded molecule. However, nucleic acids are more stable when paired. To achieve stability, RNA strands will fold back on themselves, pairing up A:U and C:G, similar to DNA. The shape of the RNA molecule often dictates its function.

High-Energy Compounds Power Cellular Activity

Life requires energy. Most often energy is available in spurts, rather than as a continuous stream all day long. We eat food, which our bodies convert to usable energy. Soon after a meal, lots of this energy circulates in the blood, but without a way to store the excess, we would have to eat almost continuously. Our energy storage system provides short- and long-term storage. Short-term energy storage uses a high-energy system that is reversible and instantly available. The most common storage is **ATP**, or **adenosine triphosphate**. ATP powers all cellular activity, from forming proteins to contracting muscles (see **Figure 3.18**). Long-term storage includes glycogen in muscles and liver, and triglycerides packed into specialized storage cells called **adipocytes**.

adenosine triphosphate (ATP) The primary energy molecule that can be used to perform cellular functions.

adipocytes Specialized cells (fat cells) that store large quantities of lipid.

ATP is composed of an adenine bonded to a ribose sugar with three phosphates attached. These phosphate bonds carry a lot of energy in their covalent bonds. When ATP is hydrolyzed, the third phosphate bond breaks, releasing inorganic phosphate (P_i) and the energy that held the ATP molecule together, forming **adenosine diphosphate (ADP)**. This released energy drives cellular activity. The ATP–ADP energy storage system is readily available and renewable. When glucose is broken down, the released energy can be used to recombine the inorganic phosphate to the ADP, generating a new ATP molecule.

adenosine diphosphate (ADP) The molecule that results when ATP releases one phosphate group.

Without chemistry, there is no life, but how does life emerge from the many molecules we have examined? In the next chapters, we will look further up the hierarchy—to cells, tissues, and organs—to see the basic organization of an organism.

CONCEPT CHECK

STOP

1. **What** are the four main categories of organic compounds?
2. **What** are the main roles of carbohydrates, lipids, proteins, and nucleic acids in the body?
3. **How** does ATP store energy?

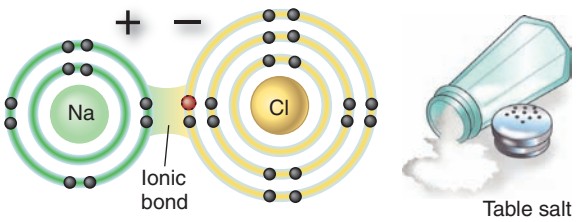
Summary

THE PLANNER

1 Life Has a Unique Chemistry 44

- All life is based on the chemical **elements**. The four most common elements in living organisms are carbon, hydrogen, oxygen, and nitrogen. The remainder of the elements that comprise living organisms appear in small, or trace, amounts only.
- The atoms of any particular element contain a specific number of protons in the nucleus, as well as a cloud of electrons around the nucleus. The electrons in the outside shell, or valence, determine the chemical reactivity of an atom.
- Elements are joined by chemical bonds. As shown in this illustration, strong, ionic bonds result from the attraction of positive and negative **ions**. Equally strong covalent bonds are formed when atoms share electrons. Unequal sharing of electrons produces a polar covalent bond, resulting in a polar molecule like water. Hydrogen bonds are weak interactions between adjacent hydrogen-containing polar molecules. The weakest forces known that hold chemicals together are van der Waals forces. These are extremely weak, impermanent electrical charge attractions formed as electrons whirl in their clouds. Transient negative charges are pulled toward equally transient positive portions of molecules. These charges change and disappear as electrons continue their whirling dance.

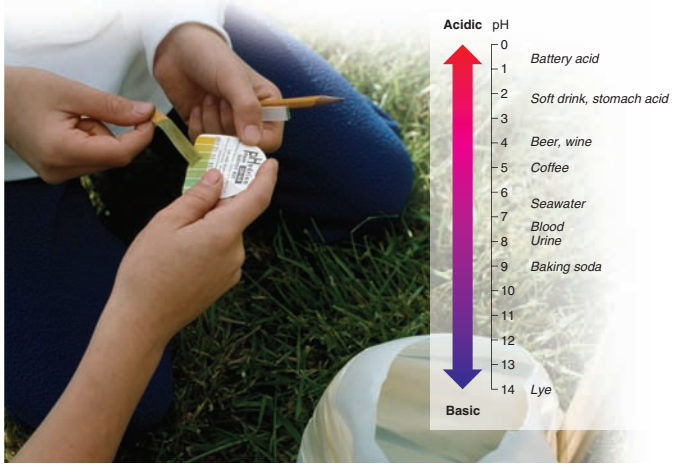
Figure 3.3



2 Water Is Life's Essential Chemical 51

- Water has many necessary characteristics for life, which trace back to the molecule's polar condition. Water is liquid at room temperature; it is a good solvent; it has a high specific heat and a high heat of vaporization; and frozen water floats. Hydrogen and hydroxide ions are released when a water molecule separates.
- The hydrogen ion concentration in any solution is indicated by the pH of that solution. As you can see here, pH 1 is highly acidic; pH 14 is extremely basic. Pure water is pH 7. Acids donate hydrogen ions to solutions, whereas bases add hydroxide ions. When mixed together, acids and bases usually neutralize and form water. Buffers are weak acids that stabilize the pH of solutions by absorbing excess hydrogen or hydroxide ions.

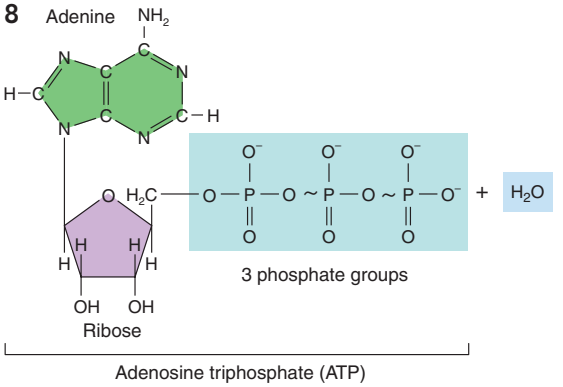
Figure 3.6



3 There Are Four Main Categories of Organic Chemicals 54

- Biochemistry is the study of biological molecules. The carbohydrate glucose is a key source of ready energy. Lipids store energy, serve in the cell membrane, and are the basis for sex hormones. Phospholipids make up the cell membrane, which is vital to cellular function. Proteins provide structure and chemical processing. Nucleic acids store data in our genes and transfer information.
- Proteins, the building blocks of the body, can be structural or functional. Protein function is determined by shape, which is determined by the sequence of amino acids. Millions of proteins are built using just 20 amino acids. Enzymes are protein catalysts that allow faster chemical reactions. Enzymes have an active site, where substrate molecules bind before the reaction takes place.
- Nucleic acids store and carry information in the cell. DNA is a double-stranded helix made of four bases (A, C, T, and G) and occurs in the nucleus. DNA codes for specific proteins, depending on the sequence of bases. The single-stranded molecule RNA serves mainly to carry DNA data to protein-making machinery. ATP, the energy-storage molecule inside cells, releases energy as it converts to ADP, as shown in this diagram.

Figure 3.18



Key Terms

- adenosine diphosphate (ADP) 63
- adenosine triphosphate (ATP) 63
- adhesive 51
- adipocytes 63
- alpha helix 61
- atomic mass 46
- atomic number 46
- cholesterol 56
- cohesive 51
- electron 46
- element 44
- functional group 54
- hydrophilic 51
- hydrophobic 51
- ion 46
- mass 46
- neutron 46
- peptide bond 59
- proton 46
- radioactive decay 46

Critical and Creative Thinking Questions

1. **CLINICAL CLICK QUESTION**
   Following a large traffic accident on the interstate highway in which a tanker truck carrying medical radio nucleotides overturned, the news began warning people near the area to seek medical help if they had any of the following symptoms:

   a. Nausea and vomiting
   b. Diarrhea
   c. Disorientation, dizziness, or low blood pressure
   d. Headache, fatigue, or unexplained weakness
   e. Fever
   f. Hair loss
   g. Poor wound healing

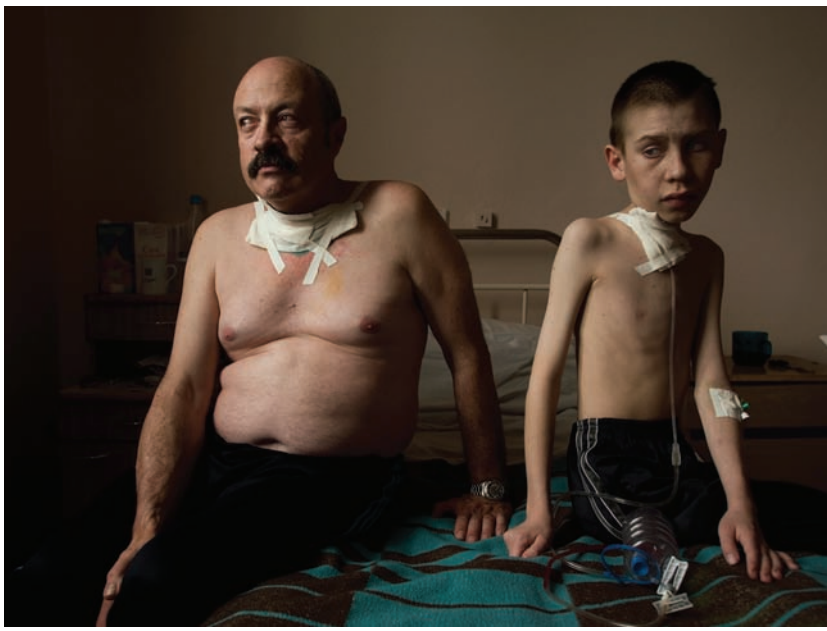
   The news alerts were very specific about the time of appearance of these symptoms. If nausea or vomiting appeared within 30 minutes of coming into contact with the accident site, victims were urged to head immediately to the nearest medical facility.

   What medical condition do these symptoms indicate?

   How might an individual passing the accident site become "infected"?

   Why did the news remind people to seek help if they experienced these symptoms up to 48 hours after the accident had been cleared?

   Visit the Web site http://www.mayoclinic.com/health/radiation-sickness/DS00432/DSECTION= symptoms to read more about these symptoms, and to learn what can be done to prevent this "sickness."
2. Choose two properties of water. Briefly describe each property and show how it contributes to a specific aspect of human life.
3. Acid rain is caused when water in the atmosphere reacts with sulfur oxides to form sulfuric acid. The acidity of typical acid rain is pH 3 to pH 5 (normal precipitation is pH 7 to pH 7.5). What is the mathematical relationship between the hydrogen-ion concentrations at each of these pH levels? How could acid rain affect biological systems?
4. Enzymes are proteins that serve as catalysts, speeding up reactions without getting used, altered, or destroyed. Enzyme function can be accelerated or slowed without damaging the enzyme itself. Review to understand normal enzyme functioning. What will happen to enzyme function if products build up in the cell? if substrate concentration decreases? if a second compound, similar to the substrate but without its reactive properties, enters the enzyme's environment? if temperature rises slightly?
5. Although they serve different functions, DNA and ATP have common elements. What structures are found in both molecules? What purpose do these structures serve in ATP? in DNA?



What is happening in this picture?

Much of our freshwater is held in glaciers. The glaciers in the Northern Hemisphere are receding at an alarming rate. Scientists realize that this loss increases the rate at which the remaining ice melts because the surface of the glacier reflects sunlight but the surface of the ocean absorbs it.

WILEY PLUS Video

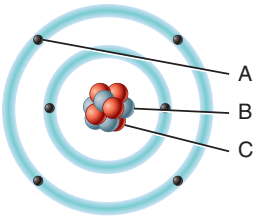
Think Critically

1. Is glacial melting an exothermic or endothermic reaction?
2. What specific properties of water allow for the formation of glaciers?
3. What properties of water allow it to buffer our global climate?

Self-Test

1. The four most common elements in the human body include _____.
   a. calcium
   b. sodium
   c. carbon
   d. nitrogen
   e. Both c and d are correct.

2. The particle indicated as A in the figure is a(n) _____.
   a. proton
   b. neutron
   c. electron
   d. orbital

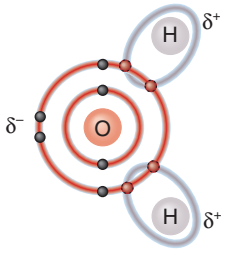


3. The particle indicated as C in the figure above carries a _____ charge.
   a. positive
   b. negative
   c. neutral

4. Of the identified particles in the figure above, particle _____ has a mass of less than 1 dalton.
   a. A
   b. B
   c. C
   d. All of the above carry a mass of 1 dalton.

5. Carbon has an atomic mass of 12.01. It has an atomic number of 6. A carbon atom nucleus has _____ neutrons.
   a. 12
   b. 6
   c. 18
   d. 4

6. The type of bond indicated here is a(n) _____ bond.
   a. ionic
   b. covalent
   c. polar covalent
   d. hydrogen

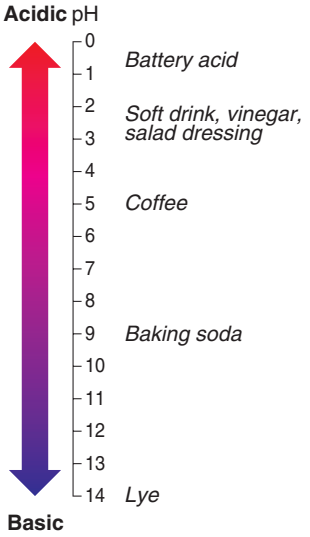


7. Some atoms are held together in compounds by attractive forces of positive and negative charges. Which of the following bond types rely on these attractive forces?
   a. ionic bond
   b. covalent bond
   c. hydrogen bond
   d. All of the above utilize positive/negative attraction.

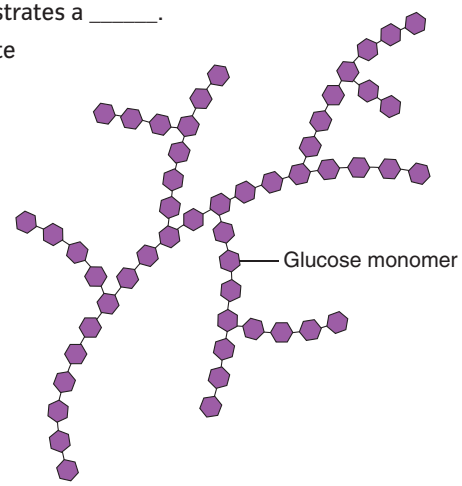
8. A substance that is attracted to water or dissolves in water is referred to as _____.
   a. hydrophobic
   b. hydrophilic
   c. cohesive
   d. adhesive

9. Water serves as a temperature buffer because it _____.
   a. is cohesive
   b. is capable of dissolving many compounds
   c. has a high specific heat
   d. has a high heat of vaporization

10. On this pH scale, what is the hydrogen ion concentration difference between human blood (pH 7) and ammonia (pH 11)?
   a. 10 units
   b. 100 units
   c. 1,000 units
   d. 10,000 units



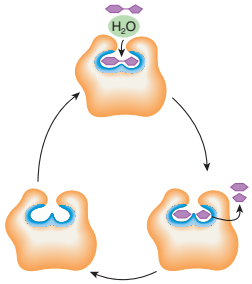
11. This figure illustrates a _____.
   a. carbohydrate
   b. lipid
   c. protein
   d. nucleic acid



12. A(n) _____ fat is a solid at room temperature and includes straight, long hydrocarbon chains with no double bonds.
   a. unsaturated
   b. saturated
   c. hydrophilic

13. The class of lipid that has both a hydrophilic and a hydrophobic end is _____.
   a. steroids
   b. eicosanoids
   c. phospholipids
   d. triglycerides

14. This figure illustrates that enzymes _____.
   a. require substrate
   b. are specific catalysts
   c. have an active site
   d. All of the above are correct.



15. In DNA, which base complements adenine?
   a. cytosine
   b. guanine
   c. thymine
   d. uracil

THE PLANNER

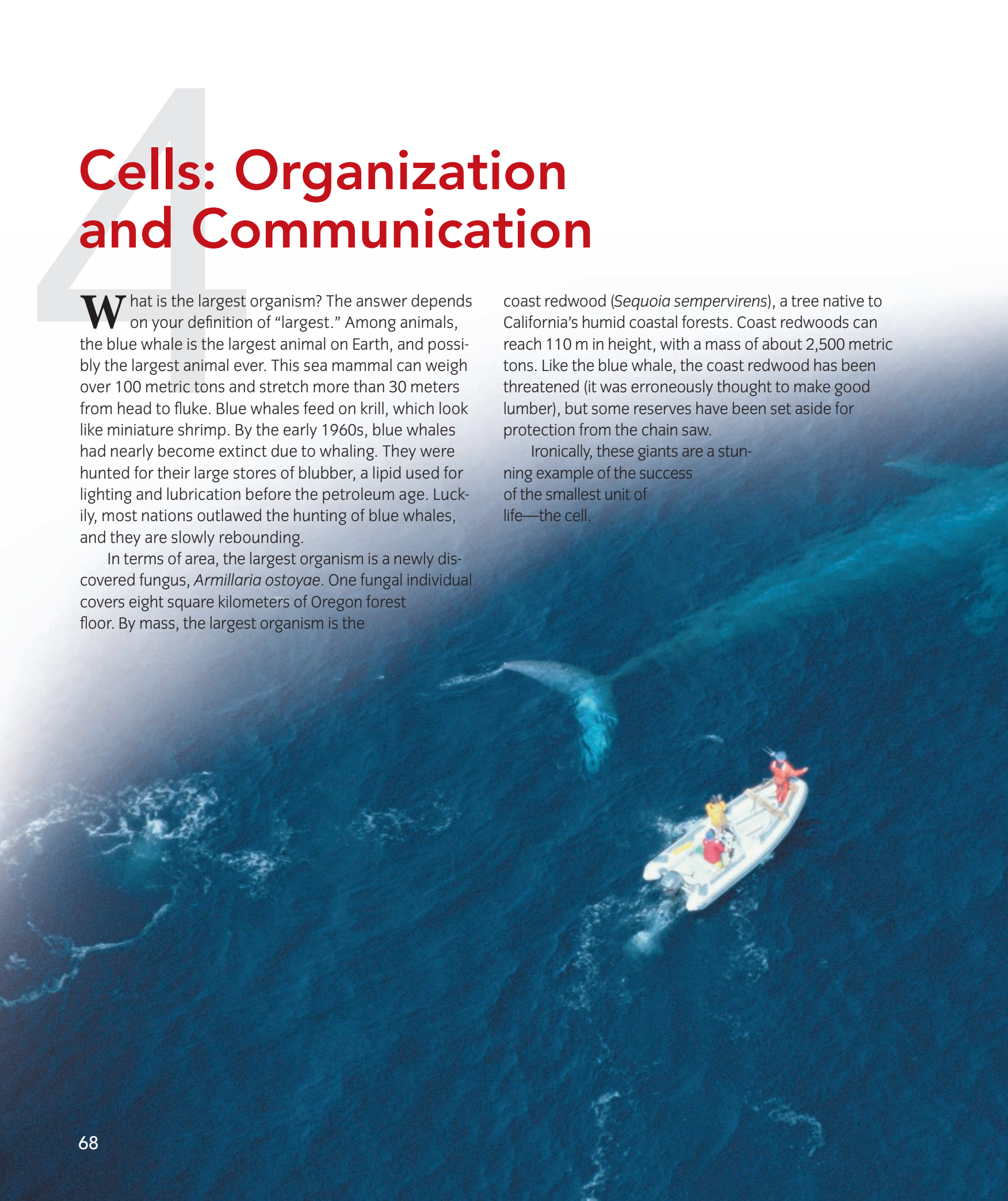
Review your Chapter Planner on the chapter opener and check off your completed work.

4 Cells: Organization and Communication

What is the largest organism? The answer depends on your definition of "largest." Among animals, the blue whale is the largest animal on Earth, and possibly the largest animal ever. This sea mammal can weigh over 100 metric tons and stretch more than 30 meters from head to fluke. Blue whales feed on krill, which look like miniature shrimp. By the early 1960s, blue whales had nearly become extinct due to whaling. They were hunted for their large stores of blubber, a lipid used for lighting and lubrication before the petroleum age. Luckily, most nations outlawed the hunting of blue whales, and they are slowly rebounding.

In terms of area, the largest organism is a newly discovered fungus, *Armillaria ostoyae*. One fungal individual covers eight square kilometers of Oregon forest floor. By mass, the largest organism is the coast redwood (*Sequoia sempervirens*), a tree native to California's humid coastal forests. Coast redwoods can reach 110 m in height, with a mass of about 2,500 metric tons. Like the blue whale, the coast redwood has been threatened (it was erroneously thought to make good lumber), but some reserves have been set aside for protection from the chain saw.

Ironically, these giants are a stunning example of the success of the smallest unit of life—the cell.



NATIONAL GEOGRAPHIC

CHAPTER OUTLINE

The Cell Is Highly Organized and Dynamic 70

- The Cell Is a Highly Organized Structure
- Millions of Years Ago, Cells Adapted to Their Environments

The Cell Membrane Isolates the Cell 73

- Movement Across the Membrane Can Be Passive or Active
- Diffusion Moves Molecules from High Concentrations to Low Concentrations
- Active Transport Uses Energy to Move Molecules Across Membranes

The Components of a Cell Are Called Organelles 78

- Organelles Continue to Play a Role in Regulating the Life and Death of Our Cells
- Flagella and Cilia Keep Things Moving
- Endoplasmic Reticulum: Protein and Hormone Manufacturing Site
- Golgi Complex: Complicated Chemical Factory
- Lysosomes: Safe Chemical Packages
- The Cell's "Library" Is the Nucleus
- Mitochondria Are Energy Factories

Cell Communication Is Important to Cellular Success 87

- Information Travels from Cell to Cell

CHAPTER PLANNER

- ❑ Study the picture and read the opening story.
- ❑ Scan the Learning Objectives in each section:
  p. 70 ❑ p. 73 ❑ p. 78 ❑ p. 87 ❑
- ❑ Read the text and study all figures and visuals. Answer any questions.

Analyze key features

- ❑ I Wonder..., p. 71
- ❑ What a Scientist Sees, p. 72
- ❑ Health, Wellness, and Disease, p. 76
- ❑ Process Diagram, p. 85
- ❑ Biological InSight, p. 86
- ❑ Ethics and Issues, p. 89
- ❑ Stop: Answer the Concept Checks before you go on:
  p. 73 ❑ p. 78 ❑ p. 87 ❑ p. 88 ❑

End of chapter

- ❑ Review the Summary and Key Terms.
- ❑ Answer the Critical and Creative Thinking Questions.
- ❑ Answer What is happening in these pictures?
- ❑ Answer the Self-Test Questions.

4.1 The Cell Is Highly Organized and Dynamic

LEARNING OBJECTIVES

1. **Outline** the cell theory.
2. **Describe** the difference between organelles and cytoplasm.
3. **Differentiate** between prokaryotic and eukaryotic cells and between plant and animal cells.

Cells are the building blocks of life. Every living thing is composed of cells, from the smallest bacterium to the blue whale or the coast redwood. These giants have vastly more cells than single-celled bacteria, and more organization, both inside their cells and out, than do those bacterial cells. All animals' structure, regardless of their anatomy, ultimately comes down to cells. This is because all animals are multicellular.

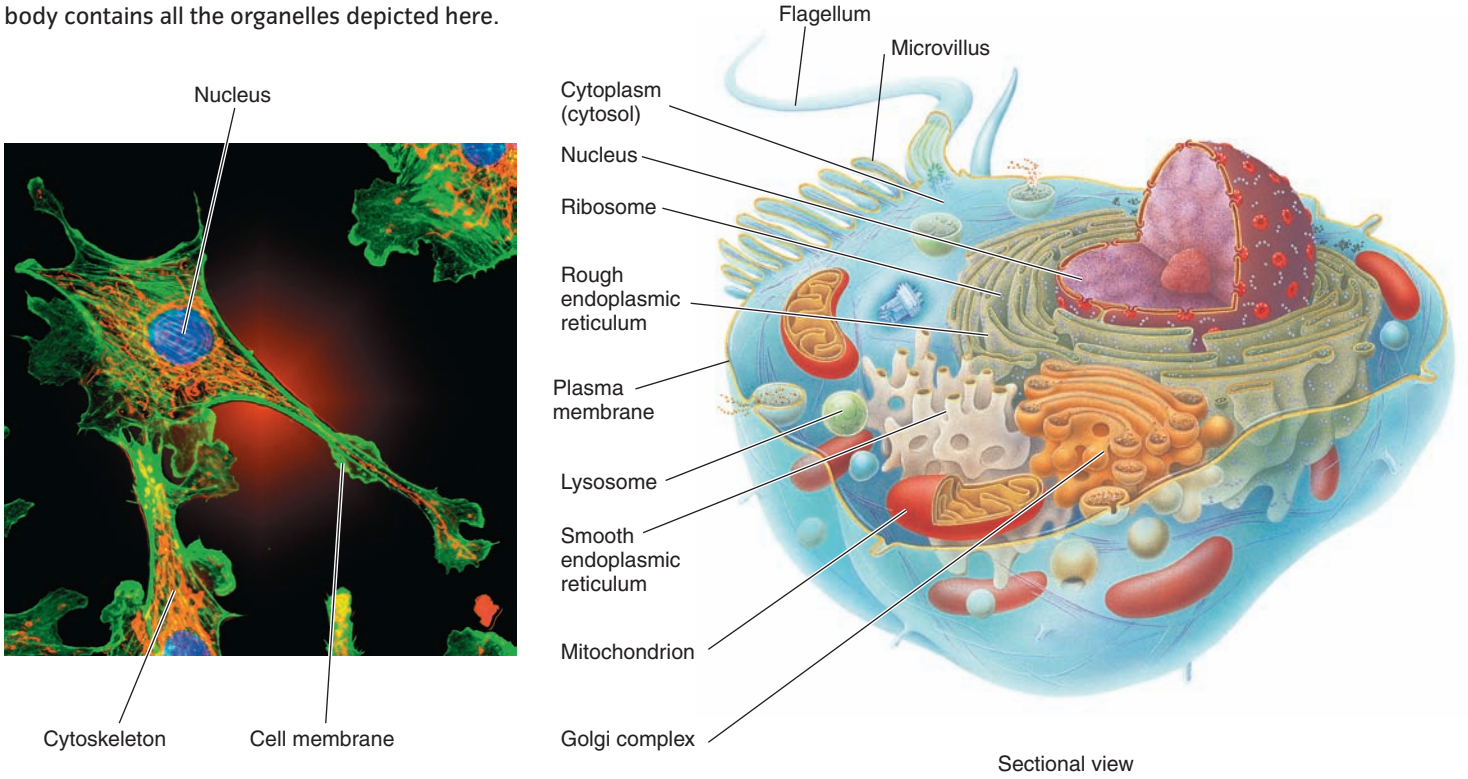
You can think of cells as packages. Because life requires certain chemical conditions, organisms must concentrate some chemicals and exclude others. Those tiny compartments with the right conditions for the many chemical reactions that sustain life are called cells (see **Figure 4.1**).

The study of cells is called **cytology**, and scientists who study cells are called **cytologists**. All cells, regardless of source, have similar characteristics, as defined by the **cell theory**. This represents the latest version of our centuries-old understanding about cells:

1. All living things are composed of cells.
2. All cells arise from preexisting cells through cell division.
3. Cells contain hereditary material, which they pass to daughter cells during cell division.
4. The chemical composition of all cells is quite similar.
5. The metabolic processes associated with life occur within cells.

Idealized animal cell • Figure 4.1

This diagram is useful in studying all the organelles. However, no one cell in the human body contains all the organelles depicted here.



Although all cells share these characteristics, they can be remarkably different in shape and size. A cell can be as large as an ostrich egg or smaller than a dust speck (a typical liter of blood, for example, contains more than 4.9×10^{12} red blood cells). Because most cells are microscopic, you need trillions to make up a typical mammal: The human body contains trillions of cells representing a few hundred different kinds, and virtually all but one type is invisible without a microscope. Our egg, the only human cell visible to the naked eye, is approximately as big as this period.

The Cell Is a Highly Organized Structure

Cells have three basic parts, as shown in Figure 4.1.

1. It is defined by a barrier called the **plasma membrane** (in animals) or cell wall (and plasma membrane in plants and bacteria).
2. Inside the plasma membrane is a fluid called **cytosol**, which supports multiple types of **organelles**, each with a function vital to the life of the cell.
3. The most prominent organelle is usually the nucleus. The cytosol and the organelles other than the nucleus are often referred to as **cytoplasm**.

The cytosol contains water, dissolved compounds, and small molecules called **inclusions**. These molecules vary with the type of cell, and may include **keratin** for waterproofing, **melanin** for absorbing ultraviolet light, and **carotenes**, which are precursors to vitamin A. See *I Wonder… What Makes a Stem Cell Different from a "Regular Cell"?* for further discussions of cells.

organelle Typically, a membrane-bound structure suspended in the cytosol; hair-like projections from the cell may also be called organelles.

keratin Tough, fibrous proteins that form hard structures, such as hair and nails.

melanin A dark brown, UV-light-absorbing pigment produced by specific cells.

carotene A yellow-orange pigment.

I WONDER...

THE PLANNER

What Makes a Stem Cell Different from a "Regular Cell"?

The term "stem cell" refers to a cell that has not yet matured and specialized. Stem cells, therefore, have the capacity to mature into any of a variety of cell types. The cells that make up your skin, muscles, heart, and intestine, for example, have specialized to perform the functions required of them. During early embryological development, however, you did not have skin cells or intestinal cells. Instead you were a mass of undifferentiated, or "pluripotent," cells, each with the capacity to develop into one of the over 200 specific types of cell that make up your body. As development proceeds, the microenvironment surrounding each of these cells becomes slightly different. Even the placement of the cell can stimulate developmental changes. One cell will be completely surrounded by other cells, while another will be on the periphery of the developing mass. This subtle difference, along with chemical cues inside the cell, begins the process of differentiation. As the tissues of the body form, the cells that make up that tissue become fully committed to that developmental pathway.

Because stem cells have not yet committed to a particular tissue type, they can be coerced into forming just about any tissue of the body. Putting stem cells into a portion of the brain, and exposing them to the microenvironment of the brain, may cause them to become new brain cells. Interestingly, it is nearly impossible to cause a mature cell to reverse this process. Thus far, scientists have not been successful in creating a group of stem cells from mature precursors by altering the cell's microenvironment.

The high degree of organization and the dynamic character of the cell are evident. Inside the cell, membrane-bound compartments can be seen. These compartments are the organelles, small structures whose overall goal is to maintain cellular homeostasis. Some organelles are microscopic power plants that break down nutrients and combine them with oxygen to make electrical energy, and others are tiny chemical factories that churn out proteins. Still other organelles extend through the plasma membrane to the surface of the cell and circulate the surrounding fluid so that waste materials and nutrients can diffuse into or out of the cell.

Not only is the dynamic character and pervasive organization of cells a model of molecular engineering, but also the countless processes in the cell take place at a rate that is hard for us to comprehend. Millions of reactions happen every second. Water movement and storage is one such reaction, as described in *What a Scientist Sees: "This Baby Needs Water!"*

Millions of Years Ago, Cells Adapted to Their Environments

The first cells were less organized and less dynamic than the cells described above, lacking a nucleus and distinct organelles. They are called **prokaryotic** cells, and do not compartmentalize cell functions. Early life-forms were prokaryotic, adapting to the extreme environments of the early Earth. Today, they survive as bacteria and archaebacteria.

Plant, animal, and fungal cells are described as **eukaryotic** cells, which almost certainly adapted by taking in smaller, energy-producing prokaryotic cells. Eukaryotic cells have a nucleus and organelles. However, not all eukaryotic cells are the same—plant cells differ slightly from human cells. Because plants lack

prokaryotic Type of cell with no internal membrane-bound compartments, usually having only genetic material as organelles.

eukaryotic Cell that contains a distinct membrane-bound nucleus.

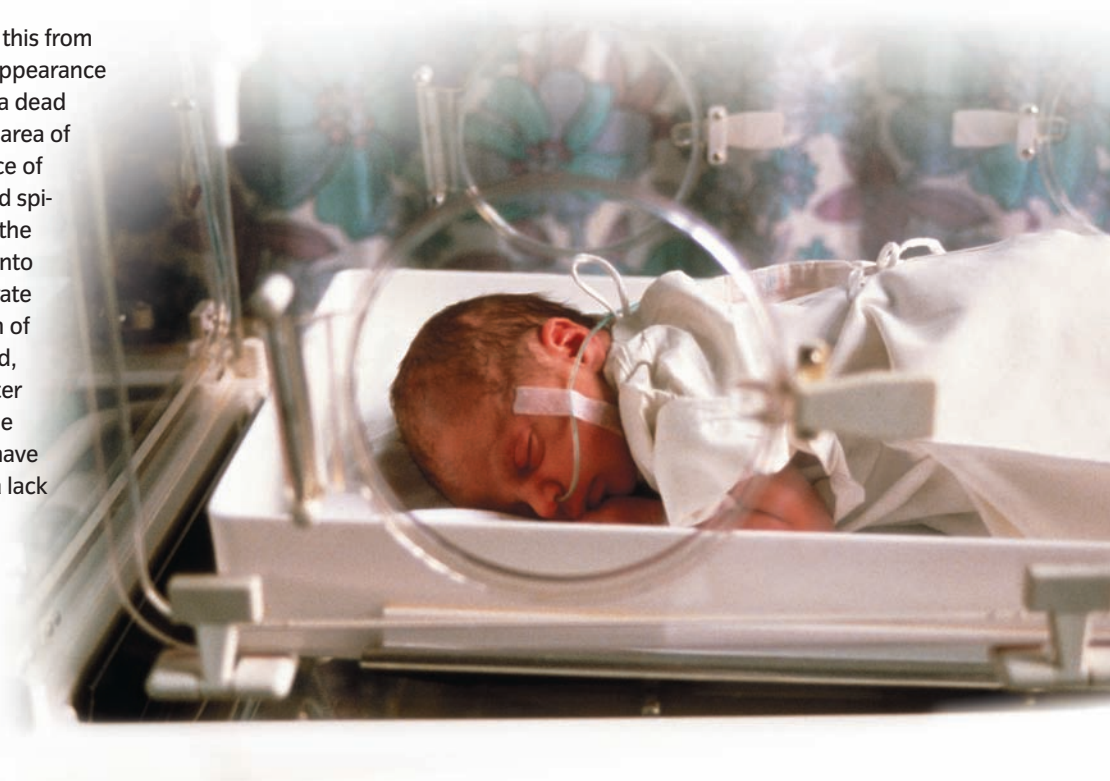
WHAT A SCIENTIST SEES

THE PLANNER

"This Baby Needs Water!"

Any medical professional can easily determine this from looking at the skull of this baby. The sunken appearance of the "soft spot" in the front of the baby's skull is a dead giveaway for a trained scientist. Normally the soft area of a baby's skull is plumped outward by an abundance of cerebrospinal fluid circulating around the brain and spinal cord. Cerebrospinal fluid is formed by filtering the liquid portion of the blood. With less water taken into the body, there will be less water available to hydrate the blood and the cells of the body. The cytoplasm of the cells will equilibrate with the water in the blood, causing the body cells to lose water. With less water in the blood, there will be less fluid available for the formation of cerebrospinal fluid. Because infants have a larger surface area to volume ratio than adults, a lack of water intake is far more critical to their health.

Using what you know of osmosis, describe the effects on the cells of the body when not enough water is present in the diet. In which direction would you expect water to move—into or out of the cells? What would you expect to occur, at the cellular level as water is added to this baby's system?



the skeletal support found in most animals, their support arises from cell walls that surround their cells. Plant cells have an organelle not found in animal cells, a central vacuole that maintains cell pressure. Many plant cells have chloroplasts—organelles where photosynthesis and energy production occurs—and many believe that chloroplasts originated as bacteria that were "adopted" by the plant cell.

CONCEPT CHECK STOP

1. **What** are the five statements that make up the cell theory?
2. **What** is the difference between organelles and cytoplasm?
3. **How** do plant cells and animal cells differ?
   How do prokaryotic and eukaryotic cells differ?

4.2 The Cell Membrane Isolates the Cell

LEARNING OBJECTIVES

1. **Discuss** the structure of the cell membrane.
2. **Explain** movement across the membrane, both passive and active.
3. **Define** osmosis, and relate it to the actions of hypotonic and hypertonic solutions.
4. **Compare** the subtle differences in the main categories of active transport.

phospholipids Compounds containing phosphoric acid and a fatty acid.

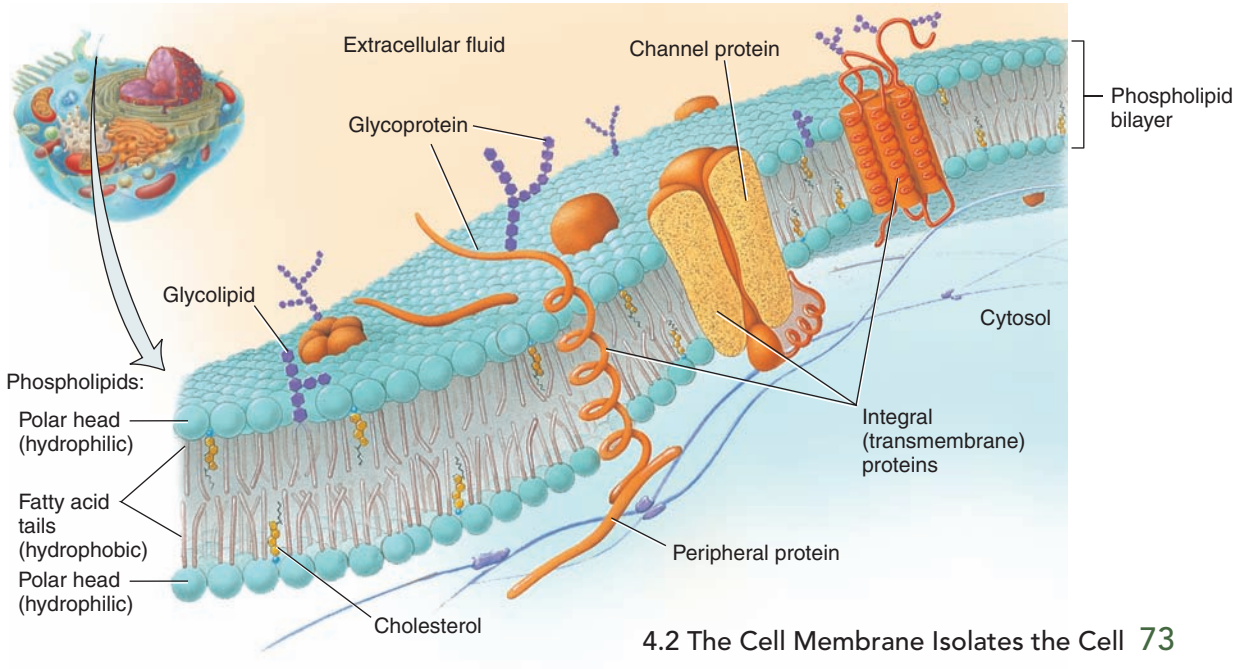
glycoprotein Protein plus a carbohydrate.

glycolipid Lipid plus at least one carbohydrate group.

The obvious place to start studying cellular anatomy is the plasma membrane, the structure that separates the cell from the extracellular fluid. This membrane is composed of two layers of **phospholipids**, interspersed with proteins, fats, and sugars, as shown in **Figure 4.2**. The phospholipids are arranged in a double layer, or bilayer, with the **hydrophilic**, water-loving heads (the charged, phosphate ends of the molecule) oriented toward the aqueous environment both inside and outside the cell. The **hydrophobic**, water-fearing, nonpolar, lipid portions of the molecules are sandwiched in the center. Some of the proteins and lipids associated with the cell membrane have sugars attached to their external surface and are called **glycoproteins** and **glycolipids**.

Cell membrane • Figure 4.2

The cell membrane is composed of a phospholipid bilayer supporting embedded proteins. Sugar attached to lipids (glycolipids) or attached to proteins (glycoproteins) coat the surface of the cell.



The glycoproteins and glycolipids form a layer called the **glycocalyx**, which is unique and defines the cell as belonging to a specific organism. Both blood type and tissue type are defined by the specific structures on the glycocalyx. For example, each person's white blood cells carry a group of identifying proteins called the human leukocyte antigens (HLAs) that serve as markers indicating that our cells belong to us. HLA is used to match tissues before organ transplants. Because HLA is inherited, if we need a transplant, we can often find a close tissue match within our immediate family.

The cell membrane is not a static structure. At 37°C, its phospholipids are liquid, not solid, so the basic structure of the membrane is a continually swirling fluid with a consistency similar to olive oil or light machine oil. Cholesterol, a necessary component of the cell membrane, helps to maintain this viscosity by interfering with the movement of the fatty acid tails of the phospholipid. The proteins embedded in the membrane are in constant motion, floating around in the fluid phospholipid bilayer. Picture a beach ball covered in Vaseline and rolled in the sand. As the Vaseline "membrane" warms in the sun, it will begin to flow around the ball (representing the cytosol of the cell), causing the embedded sand grains to swirl with it. Similarly, the glycocalyx and embedded proteins in the fluid phospholipid bilayer swirl around the cell membrane.

Movement Across the Membrane Can Be Passive or Active

The phospholipid bilayer defines the cell and protects it from the aqueous environment. Without membrane lipids, the cell would literally disintegrate, much like a cracker dropped into a glass of juice. However, the plasma membrane cannot maintain cellular homeostasis unless it allows some compounds into and out of the cell. In fact, rather than being a simple plastic bag, the membrane is a selectively **semipermeable** barrier that allows nutrients to enter the cell and waste and secretory products to exit it. Some ions and molecules cross freely; others can be moved across the membrane with the expenditure of energy; and still others cannot cross at all. Movement across the membrane can be either passive or active.

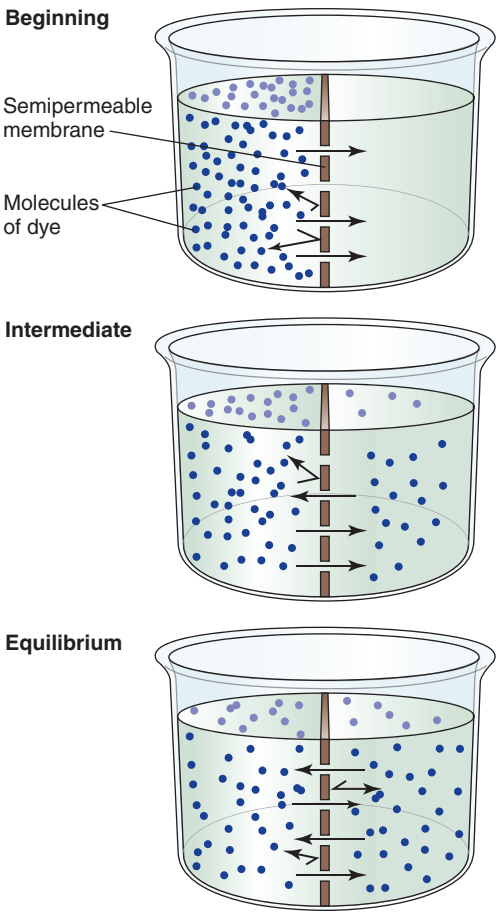
Passive movement includes **filtration**, **diffusion**, and **facilitated diffusion**. None of these activities requires the cell to expend energy. Filtration is the movement of solutes in response to fluid pressure. Your kidneys separate waste products from the blood via filtration.

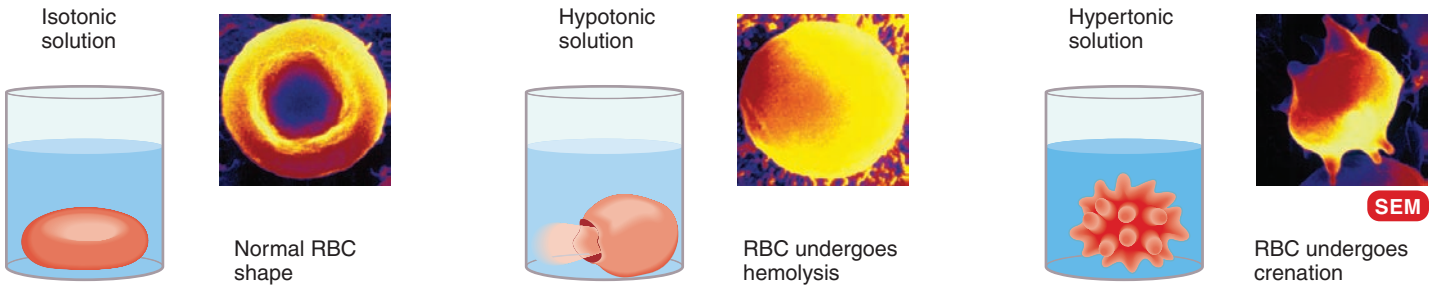
Diffusion Moves Molecules from High Concentrations to Low Concentrations

Diffusion is the movement of a substance toward an area of lower concentration. Open a perfume bottle and set it in the corner of a room. Within a short time, the perfume will diffuse from the bottle and permeate the room. Warm the room or the perfume in the bottle, and the diffusion speeds up. Diffusion results from the random movement of the molecules, which eventually tends to balance out the molecule's concentrations, as shown in **Figure 4.3**. The same phenomenon occurs

Diffusion • Figure 4.3

At equilibrium, net diffusion stops, but the random movement of particles continues.





Hypotonic and hypertonic solutions • Figure 4.4

Osmosis can occur quite rapidly when cells are placed in hypotonic or hypertonic solutions. Hemolysis is an almost instantaneous process when a red blood cell (RBC) is placed in a hypotonic solution. Crenation (the shriveling of red blood cells) in hypertonic solutions takes less than two minutes.

continuously in your cells. Lipid-soluble compounds and gases can diffuse across the cell membrane as if it weren't there, traveling right through the phospholipid bilayer. The driving force for the movement of oxygen from the atmosphere into the deepest tissues of the body is simple diffusion.

While lipid-soluble molecules can diffuse freely through it, the phospholipid bilayer blocks the diffusion of **aqueous**, or water-soluble, solutes. This is a potential problem, as many aqueous solutes, such as glucose, are essential compounds that must be able to penetrate the cell membrane. To solve this problem, the lipid bilayer has **integral** and **peripheral proteins** that serve as channels and receptors for dissolved substances to enter and exit the cell.

integral protein A protein that spans the plasma membrane.

peripheral protein A protein that sits on the inside or the outside of the cell membrane.

solute Salts, ions, and compounds dissolved in a solvent, forming a solution; water is the most common solvent in the human body.

The most abundant compound in the body is water. To maintain homeostasis, cells must allow water to move between the intracellular fluid (ICF) and the extracellular fluid (ECF). Diffusion of water across a semipermeable membrane, such as the cell membrane, is termed **osmosis**. In osmosis, water moves in a direction that tends to equalize **solute** concentration on each side of the membrane. In effect, locations with higher solute concentrations and therefore lower water concentrations seem to "pull" water toward them.

Water cannot cross the phospholipid bilayer, so it must travel through proteins. Usually, the extracellular fluid is **isotonic** to the cells, and water flows equally into and out of the cell through transport proteins. If you place a cell in a **hypotonic** solution (water with a lower concentration of solutes than the cytosol), the cell will take in water and may even burst. In contrast, a **hypertonic** solution (with a higher concentration of solutes), will remove water from the cell and cause it to shrivel up (see Figure 4.4). When working with individual cells, it is useful to calculate the concentration of an isotonic solution. Doing so allows you to predict water movement into and out of cells when they are placed in solutions of varying concentrations. It is worth noting that during osmosis, as water diffuses across a membrane toward areas of lower water concentration and higher solute concentration, it creates osmotic pressure. This pressure can be measured and is called **water potential**, the pressure of resting cells in an isotonic solution.

isotonic A solution with the same concentration as the cell cytoplasm.

Facilitated diffusion uses transport proteins. When solutes are transported across the membrane down their concentration gradients (from high concentration to low concentration) by **transport proteins**, no energy is expended, as is the case for simple diffusion. However, this type of movement requires a transport protein to facilitate the diffusion. This is the main avenue through which

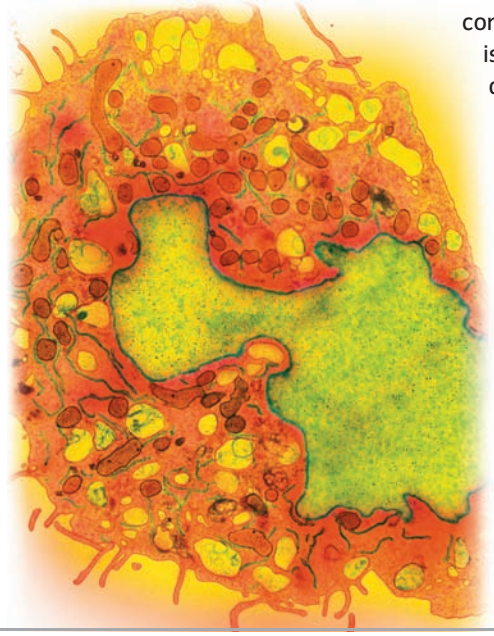
HEALTH, WELLNESS, AND DISEASE

THE PLANNER

Malfunctioning Organelles Can Be Life Threatening

The human body is only as strong as the weakest link in its homeostatic chain. Although extremely small, organelles that do not function properly are that weak link. Two of the more problematic organelles are the mitochondrion and the lysosome.

Mitochondria carry their own DNA, coding for 37 of the approximately 900 genes required to produce ATP (Adenosine triphosphate, or cellular energy). Mutations in the mitochondrial DNA occur just as they do in human DNA. A mutated mitochondrion is capable of producing daughter mitochondria, each of which carries that same mutation. Symptoms of mitochondrial disorders are most often seen in skeletal and heart muscle, glands, and the brain. Patients experience muscle spasms, muscle weakness, and stroke-like episodes. Interestingly, these symptoms increase with age, as cell division continues. As the percentage of mutated mitochondria goes up in the cells of a tissue, the ability of that tissue to function properly goes down. Charcot-Marie-Tooth disease is a mitochondrial disorder in which the nerves that reach the hands and feet are compromised. Another mitochondrial disease is MIDD, or mother inherited diabetes and deafness. In this disease, hearing loss accompanies the usual glucose imbalances typical of diabetes.

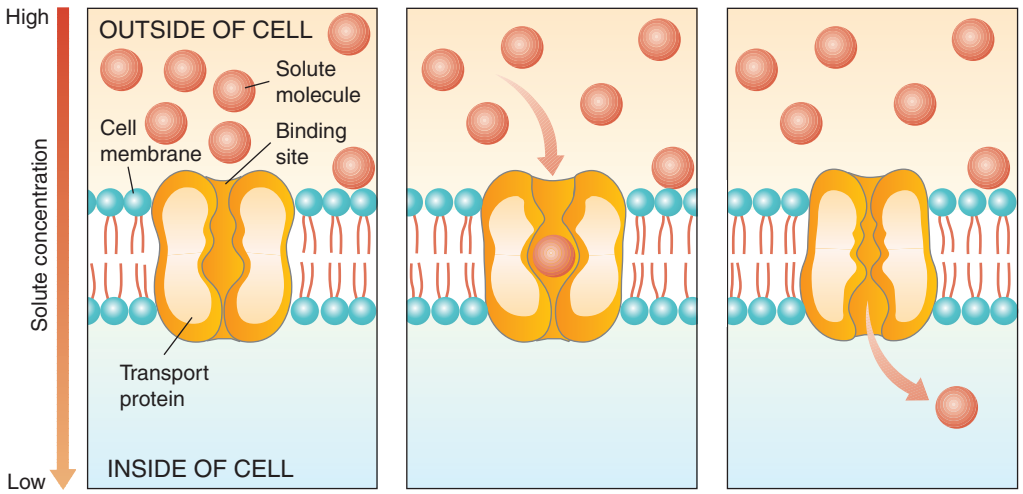


Lysosomal storage diseases are inherited diseases characterized by a buildup of undigested wastes within lysosomes. This buildup will eventually shut down the lysosome, forcing the cell to produce more lysosomes. Eventually the cell will fill with inactive lysosomes and will not be able to perform as it should. There are over 40 lysosomal storage diseases currently described. Each one is characterized by the inability to break down a specific macromolecule. In most cases, the life expectancy of the patient is limited.

glucose is moved into cells. After a meal, blood glucose is higher than cellular glucose. However, in order to diffuse into the cell, glucose needs a "doorway" through the phospholipid bilayer. It would make very little sense to expend energy just to get glucose into the cell to make energy (see **Figure 4.5**). Once in the cell, these compounds move to organelles. See *Health, Wellness, and Disease: Malfunctioning Organelles Can Be Life Threatening* to learn more.

Facilitated diffusion • Figure 4.5

Some molecules, such as glucose, require transport proteins to provide an easier entry into the cell.



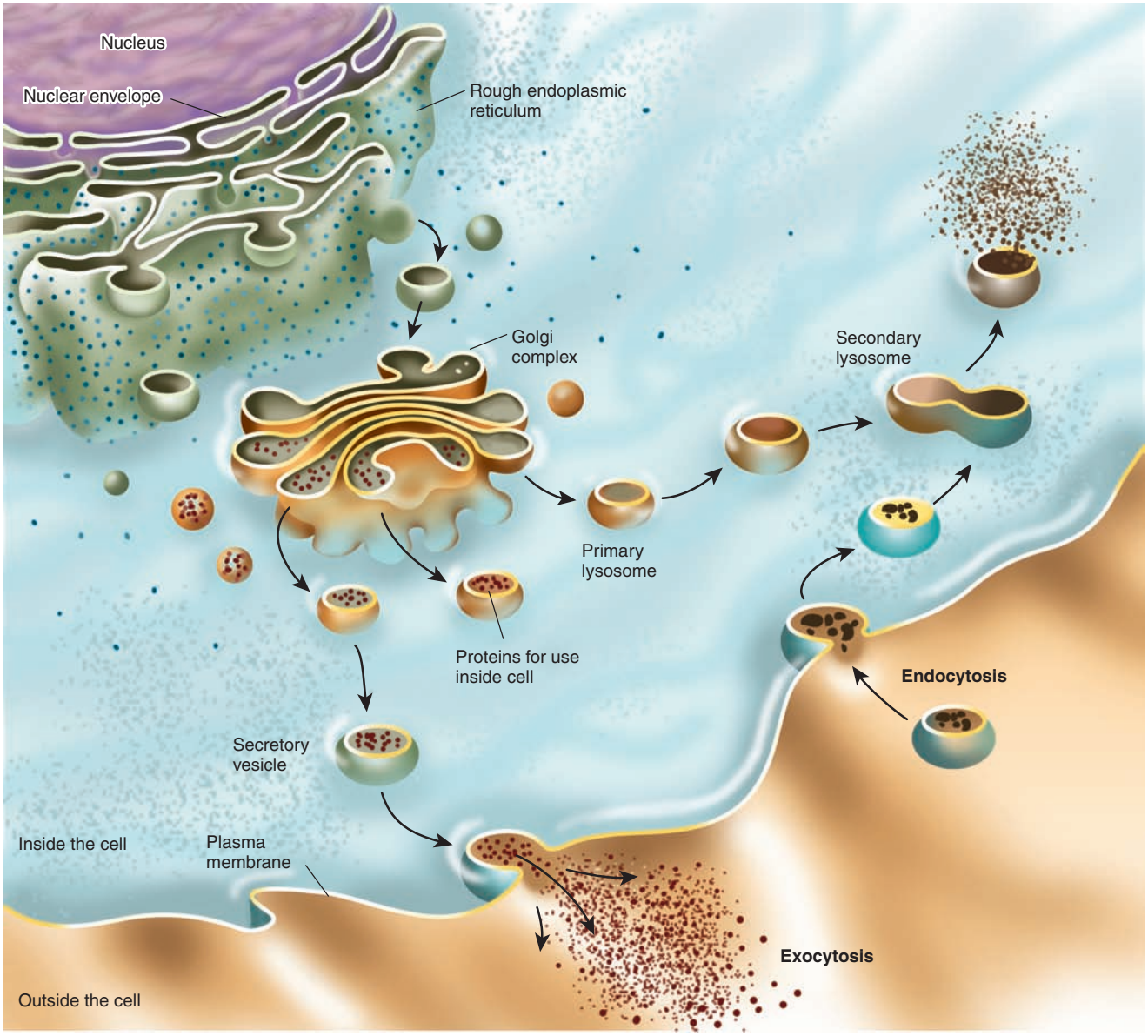
Active Transport Uses Energy to Move Molecules Across Membranes

When energy is consumed to move a molecule or ion against the concentration gradient, we call the process **active transport**, or solute pumping. Osmosis and other forms of diffusion move molecules "down" their concentration gradients without additional energy. Active transport moves molecules "up" their concentration gradients, the opposite of what you would expect from simple osmosis and diffusion. As a result, active transport is used to concentrate molecules inside cells at levels that exceed the extracellular concentration, using energy derived from the breakdown of ATP into ADP (adenosine diphosphate). Active transport accounts for the almost complete uptake of digested nutrients from the small intestine, the collecting of iodine in thyroid gland cells, and the return to the blood of the vast majority of sodium ions filtered from the blood by the kidneys.

Active transport can move atoms, ions, or molecules into the cell (**endocytosis**) or out of it (**exocytosis**) (see Figure 4.6). In endocytosis, extracellular molecules and particles are taken into the cell via vesicle formation. Just as punching a partially inflated balloon caves in the balloon wall, endocytosis begins with depression of the cell membrane. Particles in the extracellular fluid flow into the

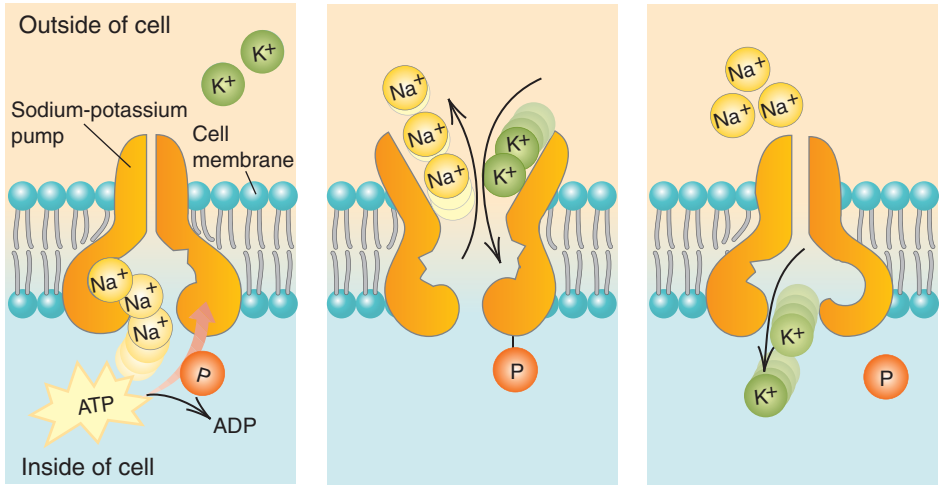
Endocytosis and exocytosis • Figure 4.6

The pathway on the left indicates movement from the rough endoplasmic reticulum through the Golgi complex to the plasma membrane. This is exocytosis. The pathway to the right indicates the flow of endocytosed particles.



Sodium/potassium pump • Figure 4.7

The sodium/potassium pump transfers two potassium ions into the cell for every three sodium ions it removes. The movement of ions happens simultaneously.



new dimple and get trapped within the vesicle that forms when the two sides touch and are pinched off inside the cell.

Exocytosis is used to remove secretory products or waste products from the cell. Vesicles form within the cell, usually from one of two organelles, the Golgi apparatus or a lysosome. Each of these vesicles travels to the inner wall of the cell membrane and fuses with it (think of two soap bubbles fusing into one larger bubble where they touch). This fusion releases the vesicle's contents into the extracellular fluid.

Often, small molecules or ions are moved by intramembrane pumps. Transport proteins may act as pumps, moving ions or small molecules in either direction across the plasma membrane. For example, calcium ions are typically transported via a pump. Pumps often have reciprocal functions—pumping one molecule or ion into the cell while simultaneously removing a second chemical species from the cell. For example, **sodium/potassium ATPase** (adenosine triphosphatase) acts as a common reciprocal pump, moving two potassium ions into the cell while pumping three sodium ions out of it, as shown in Figure 4.7. We will discuss this pump again when we cover neurophysiology.

CONCEPT CHECK

STOP

1. **What** are the main structural components of a typical cell membrane?
2. **How** are passive and active movements across the cell membrane different?
3. **What** is osmosis, and **how** does it relate to hypertonic and hypotonic solutions?
4. **How** do the main types of active transport differ?

4.3 The Components of a Cell Are Called Organelles

LEARNING OBJECTIVES

1. **List** the main organelles of a typical animal cell and describe their function.
2. **Explain** the crucial role played by the cell nucleus.
3. **Describe** the four major steps of mitochondrial reactions.

Each of the organelles covered in this section probably evolved as the result of cellular adaptations to changing environments. Cells that lacked some or all of these organelles almost certainly had a harder time successfully competing with cells that had them, so each organelle played a role in the long-term success of the cell and, in turn, the multicellular organism.

Organelles Continue to Play a Role in Regulating the Life and Death of Our Cells

Cytologists used to view the cytosol as a water bath, but it is actually a highly organized chemical soup complete with a support structure called the **cytoskeleton**. The cytoskeleton lies directly underneath the plasma membrane, and is attached to it in many places. Composed mainly of three types of filaments, the cytoskeleton extends throughout the cytosol, providing shape, support, and a scaffold for suspending and moving organelles. Unlike your bony skeleton, the cytoskeleton is continuously changing shape, forming and breaking down. This gives cells a plasticity, or fluidity, that allows them to change shape or move organelles quickly.

cytoskeleton The internal framework of a cell.

The cytoskeleton has three types of protein structure: microfilaments, intermediate filaments, and microtubules. Microfilaments, the thinnest cytoskeletal structures, are responsible for cellular locomotion, muscle contractions, and movement during cell division. They also establish the basic shape and strength of the cell. Intermediate filaments are much stronger than microfilaments and protect the cell from mechanical stresses. Microtubules are long strings of the globular protein tubulin, coiled tightly into a tube. Microtubules are used as tracks for organelle movement, and are instrumental in chromosome movement during cell division. The different proteins of each cytoskeletal element are what give it a characteristic function. The microfilaments are composed mostly of actin, a protein that, under the proper conditions, will cause movement in a predictable fashion. We discuss this protein far more extensively when looking at skeletal muscle contraction. Intermediate filaments are composed of extremely tough, supportive proteins found nowhere else in the cell.

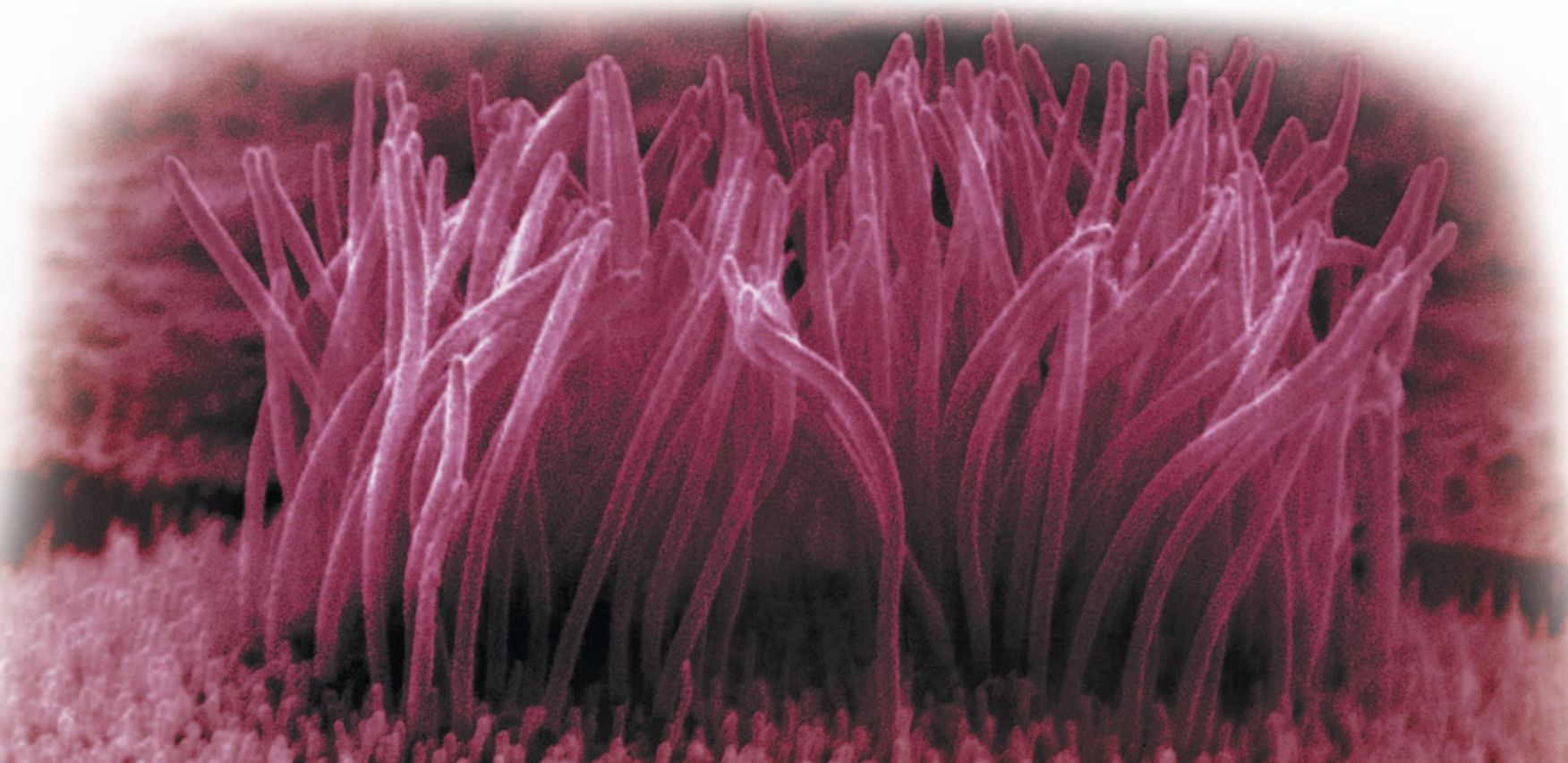
Flagella and Cilia Keep Things Moving

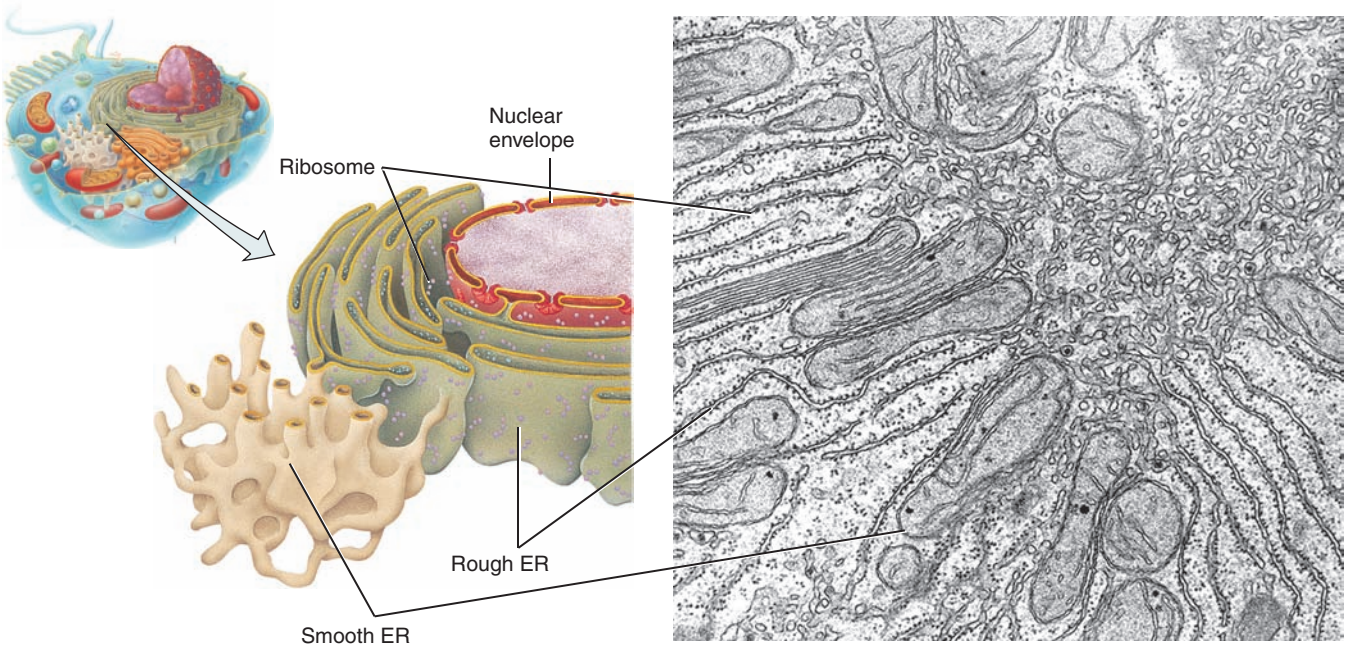
Many cells have projections from their surface that can move either the entire cell or move the extracellular fluid past the cell. **Flagella** are single, long, whip-like structures that propel the cell forward. The only human cell that moves by flagellum is the sperm.

Cilia are shorter extensions that look like hairs or eyelashes, and they are far more common in the human body than flagella (see Figure 4.8). They beat synchronously in what is referred to as a "power stroke" to move mucus across the surface of the cell or to circulate the extracellular fluid to increase diffusion. Cilia line the upper respiratory tract, moving mucus upward and sweeping out debris and pathogens.

Cilia movement • Figure 4.8

Cilia are formed from an inner core of microtubules, extending from the cytoskeleton.





Smooth endoplasmic reticulum and rough endoplasmic reticulum • Figure 4.9

The cell is packed with ER. The thin tubules without ribosomes studding their surface are the channels of the SER. The SER is concentrated in the lower left of the micrograph. As the view of the whole cell at the left shows, RER is found immediately outside the cell nucleus, while SER is a continuation of the RER tubules.

Endoplasmic Reticulum: Protein and Hormone Manufacturing Site

Within the cytosol of many cells lie networks of folded membranes, called the **endoplasmic reticulum** or **ER** (literally "within fluid network"). The membranes of the ER are directly connected to the double membrane surrounding the cell nucleus.

Human cells have two types of ER, rough and smooth. **Rough endoplasmic reticulum** (RER) is a processing and sorting area for proteins synthesized by the **ribosomes** that stud its outer membrane, as shown in Figure 4.9. Ribosomes are small non-membrane-bound organelles composed of protein and ribosomal RNA. They serve as protein factories, synthesizing proteins that may be included in other organelles or in the plasma membrane itself, or are exocytosed through secretory vesicles.

Smooth endoplasmic reticulum, or **SER**, is responsible for the synthesis of fatty acids and steroid hormones, such as testosterone. SER has no attached ribosomes. In the liver, enzymes that break down drugs and alcohol are stored in the SER.

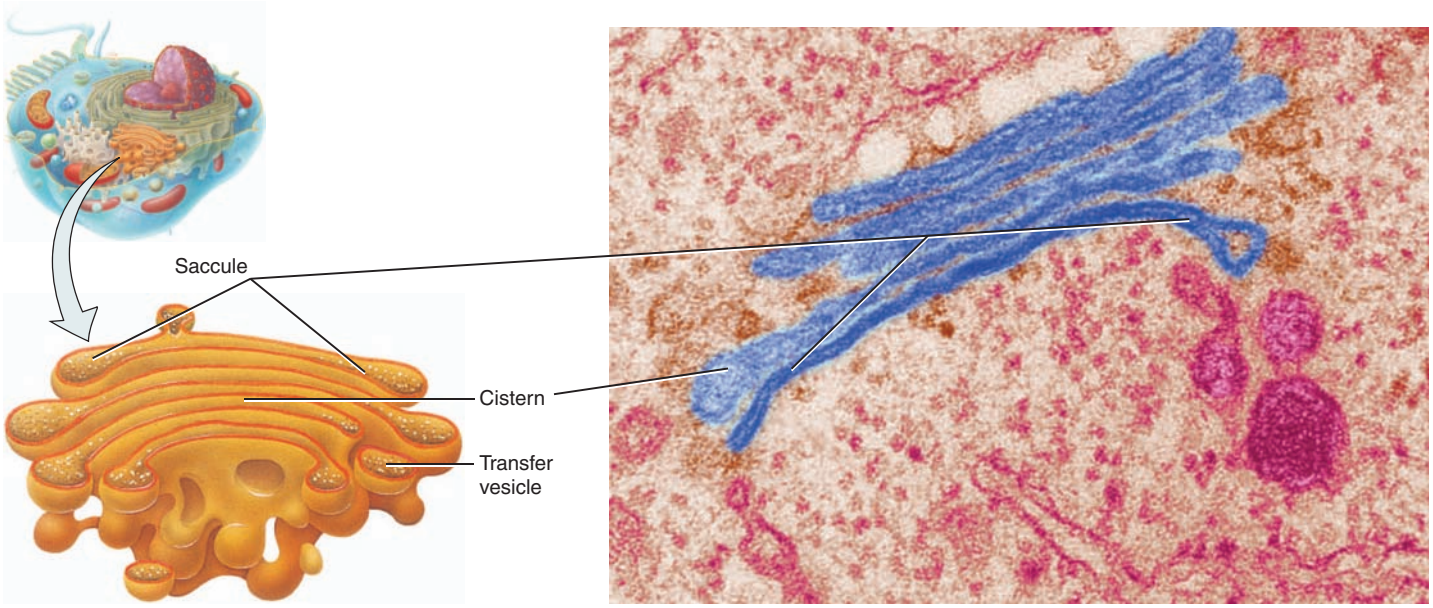
In both RER and SER, the end product is a vesicle filled with product ready for the next step in processing. These vesicles form from the ER and usually move substances from the ER to the cell membrane for exocytosis or to the Golgi complex for further packaging.

Golgi Complex: Complicated Chemical Factory

This organelle is one of the few to retain the name of its discoverer, Camillo Golgi, who discovered it in 1898. The **Golgi complex**, or Golgi apparatus, is usually found near the end of the SER and resembles a stack of pancakes called **saccules** (see Figure 4.10). These saccules are slightly curved, with concave and convex faces. The concave portions usually face the ER, and the convex portions face the plasma membrane. Vesicles are found at the edges of these saccules.

saccule Small circular vesicle used to transport substances within a cell.

The precise role of the Golgi complex is debatable. Clearly, it is involved with processing of proteins and fatty acids, but exactly how does it do that? Some scientists believe that vesicles from the ER fuse with the lowest saccule of the Golgi complex, and then the saccules



Golgi complex • Figure 4.10

The color-enhanced blue Golgi complex in this cell clearly shows the "stack of pancakes" appearance of this organelle.

"move up" in ranking toward the upper saccule. From there, the Golgi complex membrane forms a second vesicle, which transports completed proteins to their destination. Other scientists believe that the original vesicles from the ER fuse with the top saccule of the Golgi complex right from the start. The enzymes within this top saccule complete the processing of the proteins or fatty acids in the vesicle, which are then transported to their functional areas.

In either case, the vesicles that leave the Golgi complex migrate all over the cell, following paths defined by the cytoskeleton. Some fuse with the cell membrane, others fuse with lysosomes, and still others become lysosomes. It seems that the Golgi complex completes the processing of proteins and fatty acids, readying the products for use in other organelles or in the cell membrane.

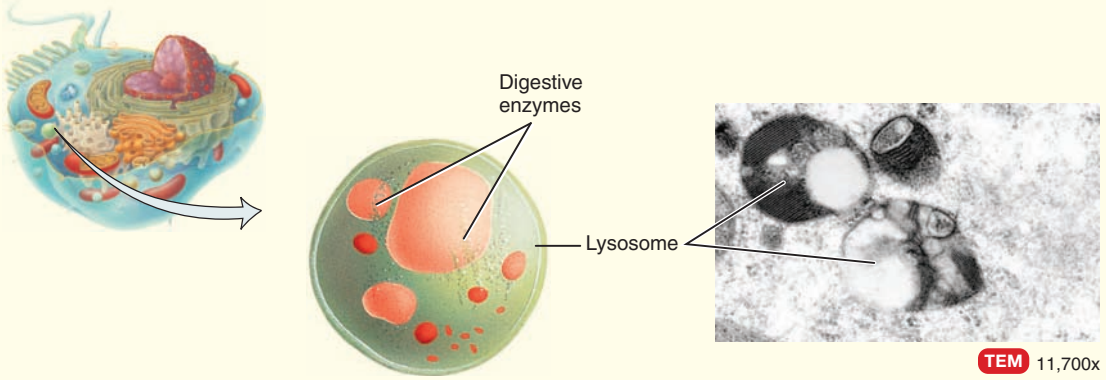
Lysosomes: Safe Chemical Packages

Lysosomes are chemical packages produced by the Golgi complex that contain **hydrolytic enzymes** powerful enough to digest an entire cell from the inside. The lysosome sequesters these digestive enzymes for use in decomposing macromolecules that have entered the cell via endocytosis, as shown in Figure 4.11. When a lysosome (*lyse* means "to break open or break

hydrolytic enzymes Proteins that help decompose compounds by splitting bonds with water molecules.

Lysosome • Figure 4.11

The lysosome sequesters digestive enzymes for use in decomposing macromolecules that have entered the cell via endocytosis, or for autolysis (self-destruction).

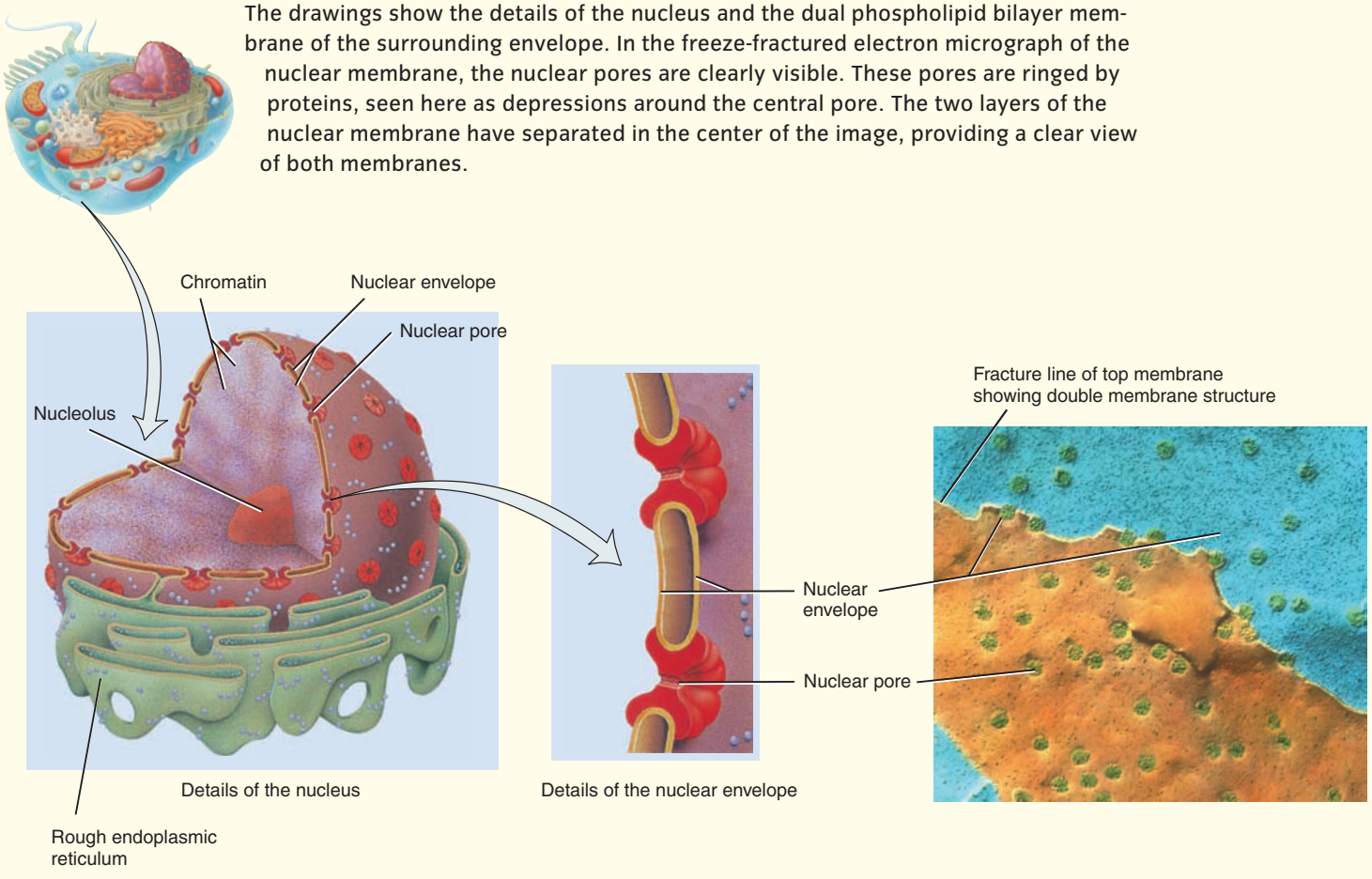


apart") fuses with an endocytotic vesicle, it pours its contents into the vesicle. The hydrolytic enzymes immediately begin breaking down the vesicle's contents. In this way, the lysosome provides a site for safe decomposition in the cell. Additionally, bacteria are routinely destroyed in the body by phagocytosis followed by lysosomal activity. If the lysosome breaks open, as happens during cell death, it will release these powerful enzymes into the cell, where they will begin to digest the cell itself. This process is called autolysis, literally self-breaking. Lysosomes can even digest parts of the body. The frog's tail is lost not by developmental changes in DNA processing but rather by lysosomes bursting and digesting cells in the tail.

The Cell's "Library" Is the Nucleus

The **nucleus** contains a cell's genetic library, and is usually the largest organelle in a cell (see **Figure 4.12**). (Mature human red blood cells, however, have no nucleus.) This organelle is approximately 5 micrometers in diameter in most human cells. It is covered, like the cell itself, by a phospholipid membrane, called the **nuclear envelope**. The difference between this envelope and the cell membrane is that there are two complete phospholipid bilayers surrounding the nucleus, whereas the cell membrane is a single bilayer. The envelope is punctuated by **nuclear pores**, which allow molecules to enter and exit the nucleus. The DNA in the nucleus is analogous to the cell's library, which is "read" by molecules called RNA. After RNA makes a perfect impression of the DNA, it leaves the nucleus and serves as templates for proteins. The process of forming RNA copies of nuclear DNA is called **transcription**, which means to "write elsewhere." This process will be discussed in detail in Chapter 20.

The cell nucleus • Figure 4.12

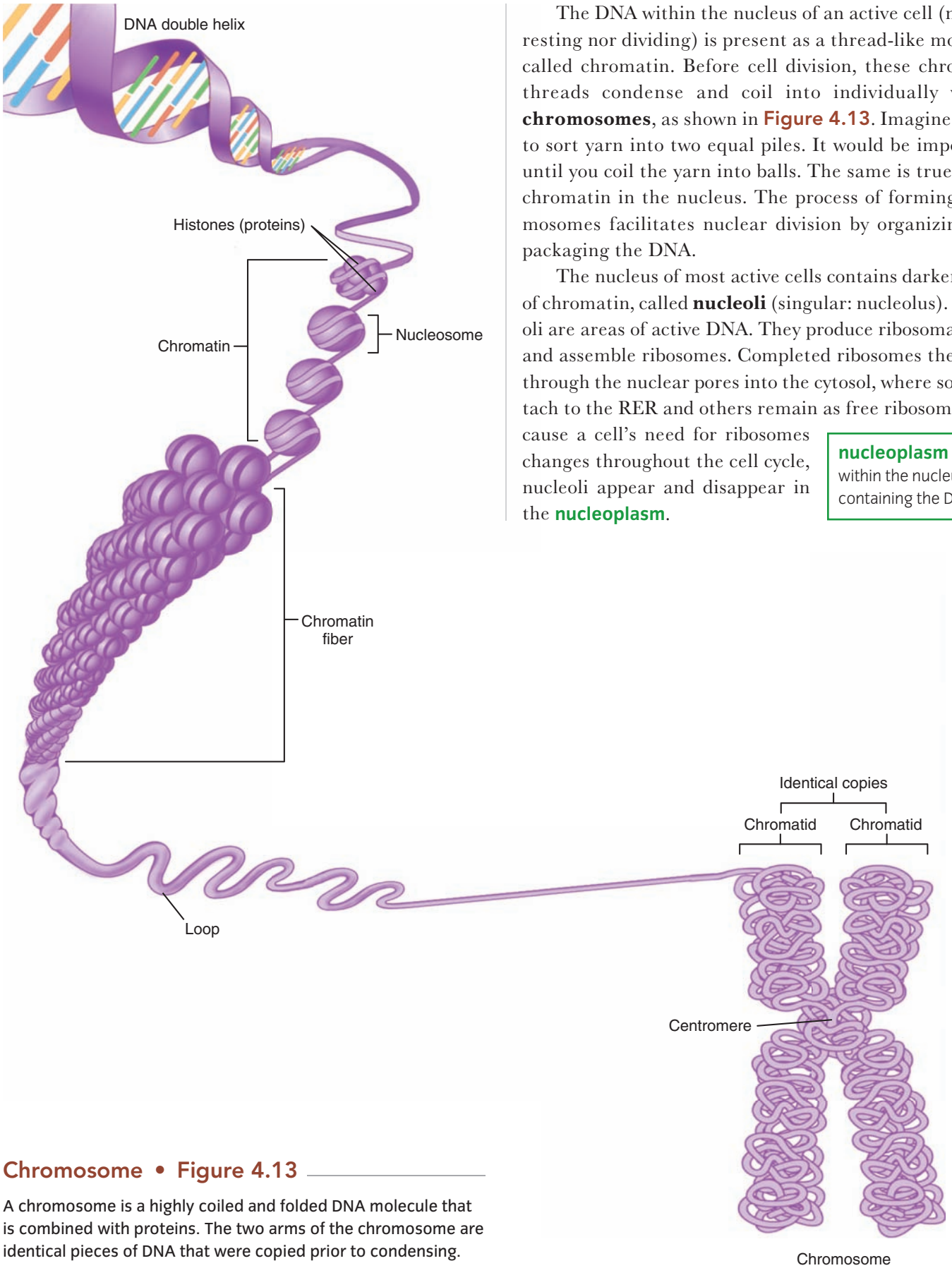


The drawings show the details of the nucleus and the dual phospholipid bilayer membrane of the surrounding envelope. In the freeze-fractured electron micrograph of the nuclear membrane, the nuclear pores are clearly visible. These pores are ringed by proteins, seen here as depressions around the central pore. The two layers of the nuclear membrane have separated in the center of the image, providing a clear view of both membranes.

The DNA within the nucleus of an active cell (neither resting nor dividing) is present as a thread-like molecule called chromatin. Before cell division, these chromatin threads condense and coil into individually visible **chromosomes**, as shown in Figure 4.13. Imagine trying to sort yarn into two equal piles. It would be impossible until you coil the yarn into balls. The same is true of the chromatin in the nucleus. The process of forming chromosomes facilitates nuclear division by organizing and packaging the DNA.

The nucleus of most active cells contains darker areas of chromatin, called **nucleoli** (singular: nucleolus). Nucleoli are areas of active DNA. They produce ribosomal RNA and assemble ribosomes. Completed ribosomes then pass through the nuclear pores into the cytosol, where some attach to the RER and others remain as free ribosomes. Because a cell's need for ribosomes changes throughout the cell cycle, nucleoli appear and disappear in the **nucleoplasm**.

nucleoplasm Fluid within the nucleus, containing the DNA.



Chromosome • Figure 4.13

A chromosome is a highly coiled and folded DNA molecule that is combined with proteins. The two arms of the chromosome are identical pieces of DNA that were copied prior to condensing.

Mitochondria Are Energy Factories

The last of the major organelles is the **mitochondrion** (plural: *mitochondria*). This bean-shaped organelle has a smooth outer membrane and a folded inner membrane, with folds called **cristae**, as seen in Figure 4.14. The mitochondria convert digested nutrients into usable energy for the body, in the form of ATP. The energy in the nutrients can be released slowly, so ATP is produced in stages as needed by the cell and the body. Virtually every move you make, every step you take, can be traced to mitochondria.

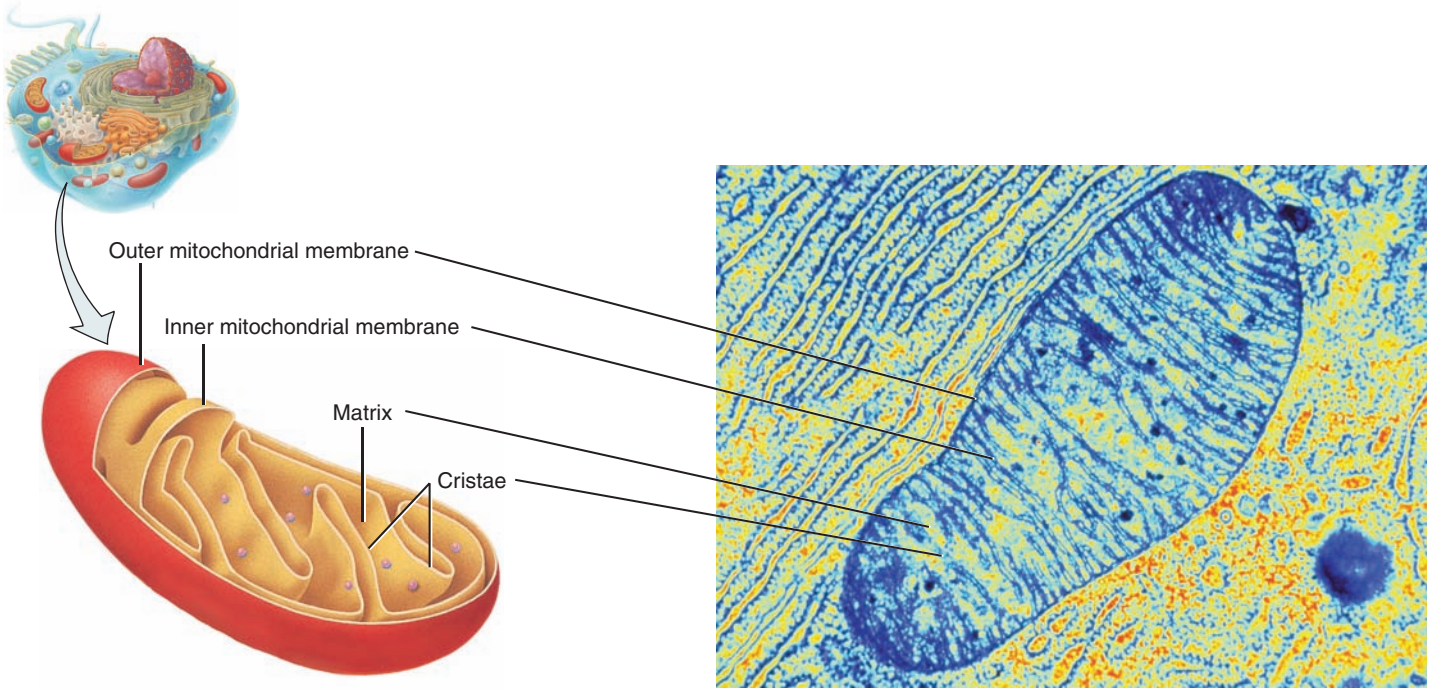
Each cell has many mitochondria, all producing the ATP your cells need to survive. ATP forms within the inner membrane of the mitochondrion (Figure 4.15). Mitochondria require oxygen and produce carbon dioxide in their endless production of ATP, and so the processes in the mitochondria are often called **cellular respiration**. In the final analysis, we inhale oxygen to serve our mitochondria, and we exhale the carbon dioxide they produce while generating ATP. Human biologists have often described ATP as a kind of molecular battery pack that gets used up and recharged every few minutes, and the mitochondria are the recharging devices.

Mitochondria break down glucose to produce ATP in four steps. The breakdown of glucose into ATP takes four steps, the first of which actually happens outside the mitochondrial walls. The other three steps take place within the mitochondria.

1. Glucose is brought into the cell via facilitated diffusion, where it is broken down in a series of chemical reactions called glycolysis. Glycolysis releases energy that is stored in two ATP molecules and two molecules of pyruvic acid.
2. Pyruvic acid then gets taken into the mitochondrion, where it is converted to acetyl co-A.
3. Acetyl co-A feeds into the Krebs cycle (also called the citric acid cycle or TCA cycle), another series of biochemical reactions that release energy from the acetyl co-A and stored in ATP, NADH, and $FADH_2$.
4. The NADH and $FADH_2$ formed during glycolysis and the Krebs cycle are transported to the inner membrane of the mitochondrion. There they are used to drive a final series of reactions called the electron transport chain. This final series converts the energy stored in the NADH and $FADH_2$ into usable ATP.

Mitochondrion • Figure 4.14

The cristae within the mitochondrion are a hallmark of this organelle. Here the inner membrane is colored blue to help distinguish the cristae.

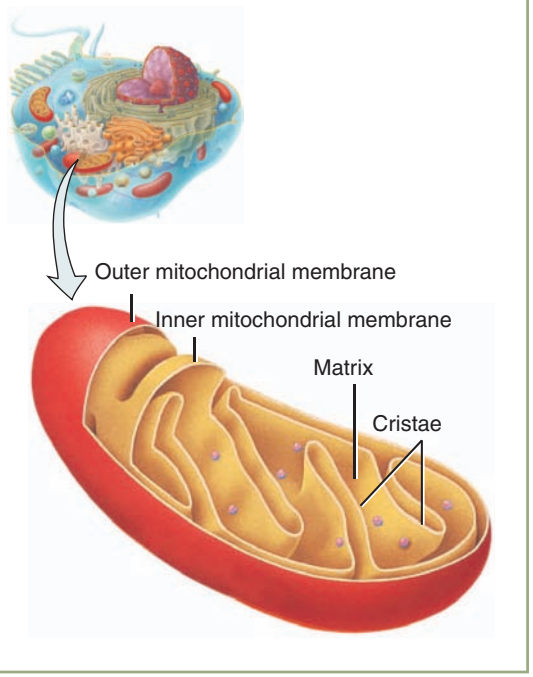


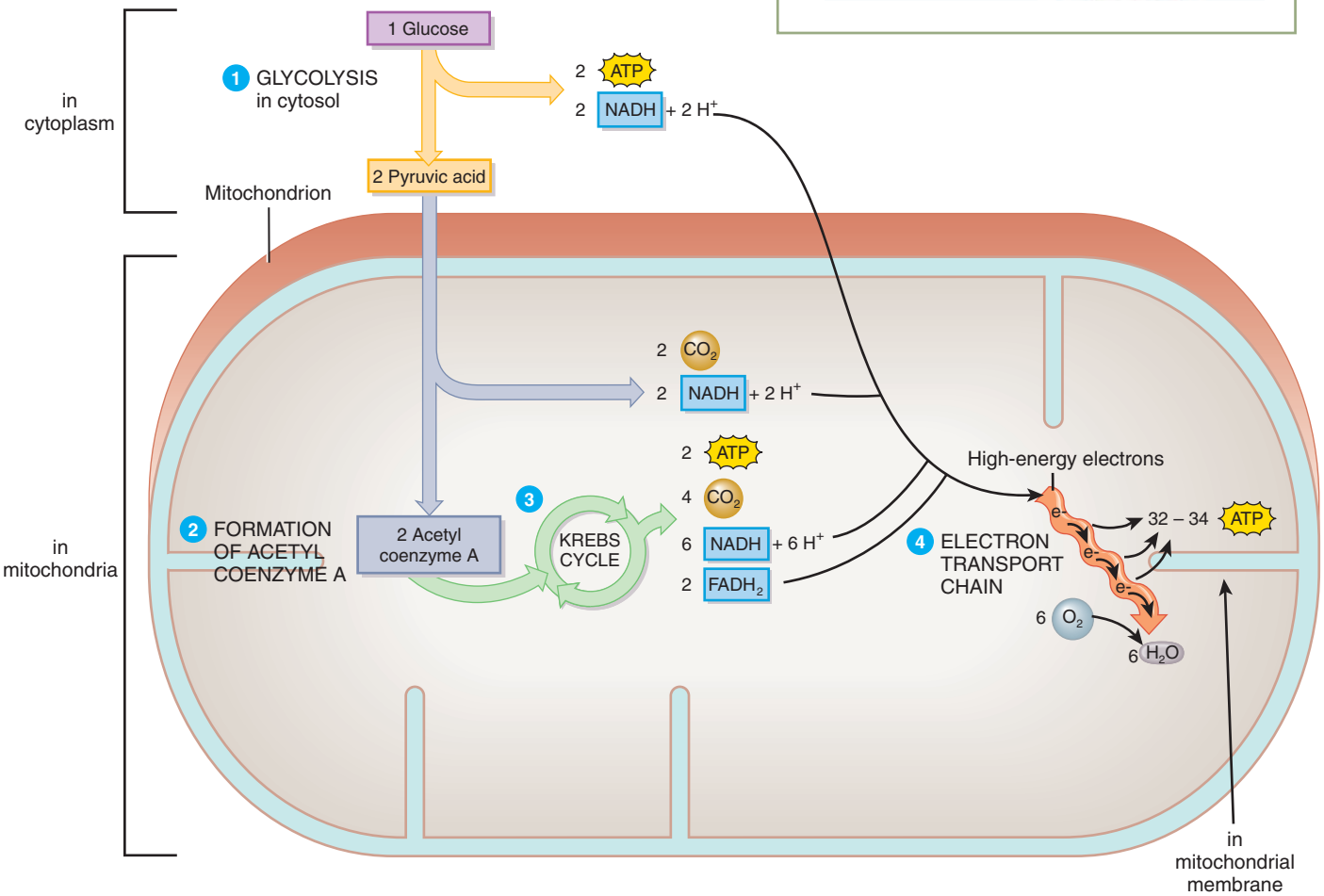
Mitochondrial reactions • Figure 4.15

THE PLANNER

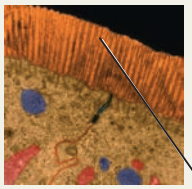
1. Glucose is broken into two pyruvic acid molecules before entering the mitochondrion. This releases 2 ATP molecules and 2 NADH molecules.
2. Acetyl co-A is formed inside the matrix of the mitochondrion.
3. Energy is released from acetyl co-A during the Krebs cycle.
4. Much more energy is released as final breakdown of the initial glucose molecule occurs in the cristae membrane.

WILEY PLUS Interactivity





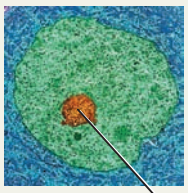
Flagellum:
Moves an entire cell.



Microvilli:
Folded parts of the cell membrane that increase the cell's surface area.

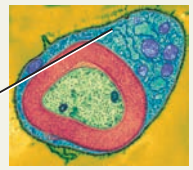
Cilium

Secretory vesicle



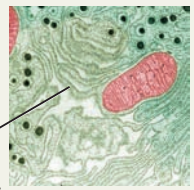
Nucleus:
Contains genes, which control and direct most cellular activities.

Nucleolus

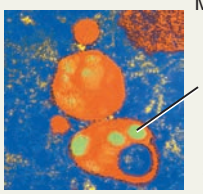


Cytoplasm:
Site of all intracellular activities except those occurring in the nucleus.

Centrioles:
Organizing center for microtubules and mitotic spindle.



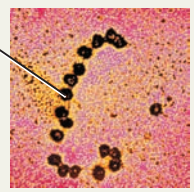
PLASMA MEMBRANE



Endoplasmic Reticulum (ER):
Rough ER is the site of synthesis of glycoproteins and phospholipids; smooth ER is the site of fatty acid and steroid synthesis.

Lysosome:
Fuses with and digests contents of vesicles; digests worn-out organelles, entire cells, and extracellular materials.

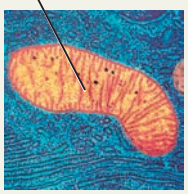
Ribosome:
Protein synthesis.



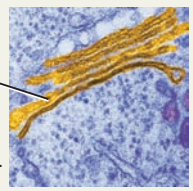
Smooth endoplasmic reticulum

Mitochondrion:
Site of reactions that produce most of a cell's ATP.

Sectional view



Golgi Complex:
Accepts proteins from rough ER; stores, packages, and exports proteins.



Mitochondria can divide, replicating these energy-producing organelles when our cells need more ATP. Cells in active tissues, like skeletal muscle and liver, have more mitochondria than cells in less active tissue. This ability to reproduce has long intrigued cellular biologists. Mitochondria resemble bacteria in size and chemical composition, and carry their own DNA to create their proteins. Some scientists hypothesize that these organelles were once free-living bacteria that evolved from a **symbiotic** relationship into a type of ultimate, intimate symbiosis. Perhaps billions of years ago, a bacterial cell traded a free-living existence for a safe and constant environment in which to carry out its life processes. In this "you scratch my back and I'll scratch yours" arrangement, the sheltering cell receives a supply of ATP in return for protecting the mitochondria, delivering oxygen to it and disposing of its waste carbon dioxide. Interestingly, mitochondria are not constantly reshuffled through sexual reproduction and are inherited only through the egg. This means the mitochondria in your body are direct descendants of your mother's mitochondria. Because of the relatively stable DNA in mitochondria, they can help trace human migrations and evolution.

symbiotic Intimate coexistence of two organisms in a mutually beneficial relationship.

See **Figure 4.16** for a summary of animal cell parts and their functions.

CONCEPT CHECK STOP

1. **What** are the main organelles of an animal cell and what are their functions?
2. **What** role does the nucleus play in the cell?
3. **What** are the four major steps of mitochondrial reactions?

4.4 Cell Communication Is Important to Cellular Success

LEARNING OBJECTIVES

1. **Explain** cellular signaling as it relates to the human body.
2. **Define** hormone.

To maintain stability and organization inside the human body, communication is essential. Cells must communicate with one another to function as a tissue. Tissues must send signals throughout the organ for the organ to function properly. Organs in a particular system must communicate to carry out the system's process. The importance of communication only makes sense. Think how little you could accomplish in your personal life without communication among individuals in your community. How would schooling prepare you for life if no one discussed what it means to be an educated citizen? What would become of government if there weren't any communication among constituents? On a more personal scale, how would your life fare without a cell phone or Internet connection? Just as society requires communication for survival, cells of the body require communication in order to maintain homeostasis.

Information Travels from Cell to Cell

The signals sent from cell to cell include information about the timing of cell divisions, the health of adjacent cells, and the status of the external environment. Cells communicate with one another via chemical messengers

or physical contact, as seen in Figure 4.17. Cell signaling can be accomplished via three routes, which differ in the speed and distance of the signal transmission:

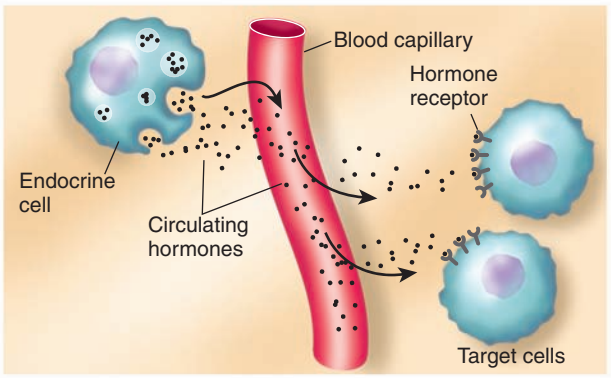
1. Circulating **hormones** can be released into the bloodstream, potentially reaching every cell. Much hormonal communication is long distance, carrying information to distant cells that will alter their functioning. For example, the pituitary gland in the center of the brain secretes a hormone that stimulates reproductive organs in the pelvic cavity.

hormone
Compound secreted in one area of the body that is active in another area; usually carried by the blood.

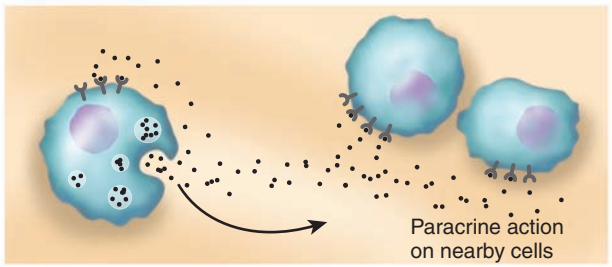
2. Local hormones, called **paracrines**, can be released to affect only cells in the vicinity. Neurons use paracrines to stimulate nearby nerve, muscle, or glandular cells by releasing short-lived chemicals called neurotransmitters. Paracrine communication is mostly used when quick responses are required. Neurons must respond instantly to information; therefore, they secrete neurotransmitters directly into the space between cells. Sending neurotransmitters into the bloodstream would be too slow for nerve impulses.
3. Cells of epithelial and muscular tissues can interact with other cells directly through physical connections at cell-to-cell junctions. **Gap junctions**, such as those between heart muscle cells, are used for instantaneous communications. They occur across very small distances and are extremely specific. Unlike endocrine communication, which has long-lasting effects, gap junction communications are immediate and short-lived. Cell-to-cell junctions occur in tissues like your skin, where cells are in direct contact with one another.

Cell signaling mechanisms • Figure 4.17

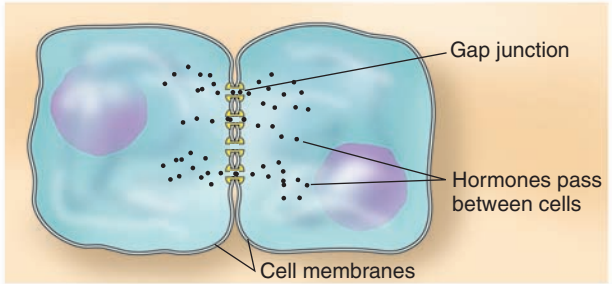
Circulating hormones are carried through the bloodstream to act on distant target cells. Paracrines act on neighboring cells. Cell-to-cell contact is the third route shown.



a. Circulating hormones



b. Local hormones (paracrine and autocrine)



c. Gap junctions

Our cells constantly send and receive messages—commands, corrections, updates, and requests. One of the best-coordinated, communication-rich events in a cell's life cycle is cell division, or **mitosis**. To carry out this complicated process, the cell must communicate with surrounding cells and its own organelles and biochemical pathways. During mitosis, DNA and organelles are duplicated, and DNA is condensed into manageable packets and sorted into separate nuclei. Then two intact cell membranes are formed, each containing all of the organelles and DNA of the parent cell. This process will be discussed in detail in Chapter 20. This complicated process adds to the difficulty of creating artificial cells. Read more about this in *Ethics and Issues: Artificial Life: Why Is It So Hard to Create?*

Another of the most significant communications in a cell's life cycle is the instruction it receives to die—a programmed death called **apoptosis**. Each minute countless numbers of your cells die and dismantle themselves. We know now that many cancer cells result from those cells' inability to respond to the programmed death command. We will see this in Chapter 11.

CONCEPT CHECK

STOP

1. **Why** is cell-to-cell communication necessary in the human body?
2. **What** is a hormone?

ETHICS AND ISSUES

THE PLANNER

Artificial Life: Why Is It So Hard to Create?

In 2002, scientists at the State University of New York at Stony Brook assembled the first synthetic virus. They downloaded a recipe from the Internet, bought a gene sequence from a mail-order supplier, and in their laboratory whipped up a batch of polio. They proved the virus's potency by injecting it in mice, which then became paralyzed and eventually died.

"[We] did it to prove that it can be done," Dr. Eckard Wimmer told the Associated Press (AP). Wimmer led the team that conducted the research and published the results in the prestigious journal *Science*. "This approach has been talked about but people didn't take it seriously. Now people have to take it seriously," he told AP.

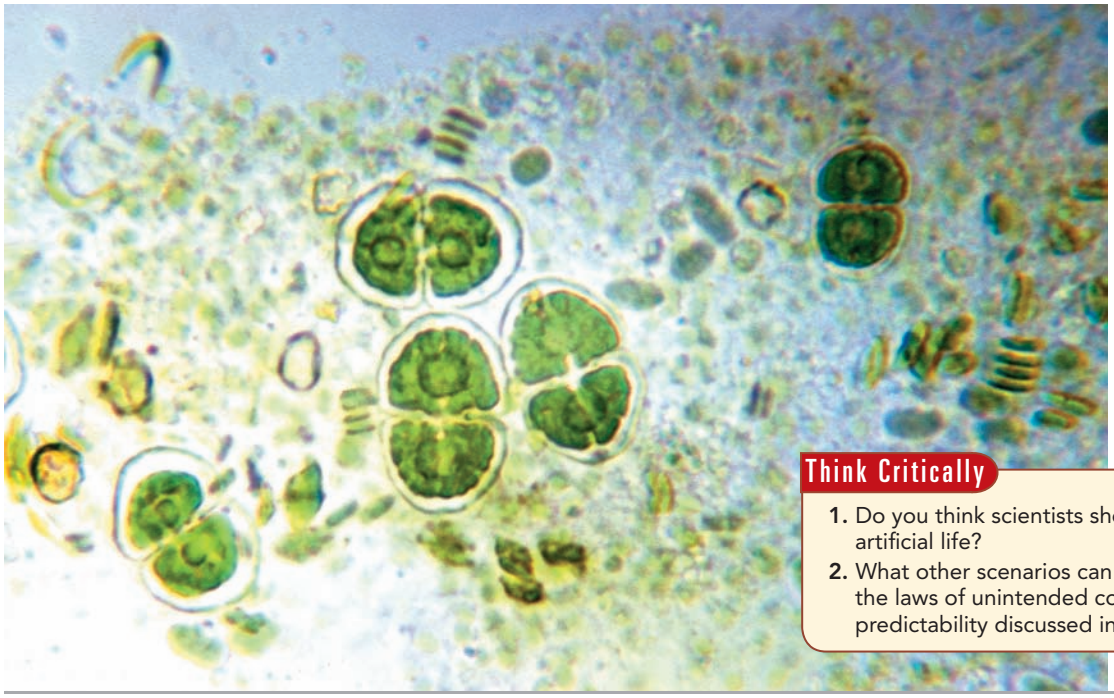
Scientists are divided over whether the experiment by Wimmer's team constitutes the "creation of life" or merely the recreation of a synthetic version of something that is not a life-form. A virus, they say, is not really alive. To create artificial life, scientists must produce a life-form that is able to reproduce and change (mutate) according to evolutionary principles in response to changes in its environment.

If this could be accomplished, would the new organism truly represent life? In addition to being able to reproduce and mutate, the creation would need an artificial membrane that successfully keeps harmful molecules out while allowing nutrients in—a membrane that "knows" what a cell needs to survive. The new organism would also need a metabolism that can take in food from the environment and convert it into energy.

Whether or not the Stony Brook experiment "created life," it did call attention to a frightening possibility. While medical science and public health programs have been working for over half a century to eliminate polio as a naturally occurring menace, scientists have shown that they can recreate this dreaded disease with cookbook efficiency using off-the-shelf materials.

The Stony Brook experiment is just one of many recent efforts by scientists in the field of "synthetic biology" to recreate life or create new life-forms. In another experiment, scientists at Rockefeller University created "vesicle bioreactors"—mixtures of fat molecules from egg whites, E. coli bacteria stripped of their genetic material, and enzymes from viruses. When new genetic material was added, this jerry-rigged "cell" was able to produce proteins. Some genetic sequences caused changes to occur in the vesicle's wall, making the wall more like a true cell's membrane.

Critical Reasoning Issues Whether or not a virus or a vesicle bioreactor constitutes the creation of new life, the key question remains: What happens when more scientists have the ability to create or recreate life-forms in a laboratory? Will they unleash alien life-forms, causing untold environmental damage? Although scientific advancement is inherently value neutral, some fear the unintended consequences of creating life where there was none. Could it be that, in the wrong hands, such knowledge could lead to bioterrorism on a massive scale?



These green alga cells appear deceivingly simple, but thus far scientists have not been able to create them in a lab.

NATIONAL GEOGRAPHIC

WILEY PLUS Video

Think Critically

1. Do you think scientists should pursue the creation of artificial life?
2. What other scenarios can you foresee if they do, given the laws of unintended consequences and the limits of predictability discussed in Chapter 1?

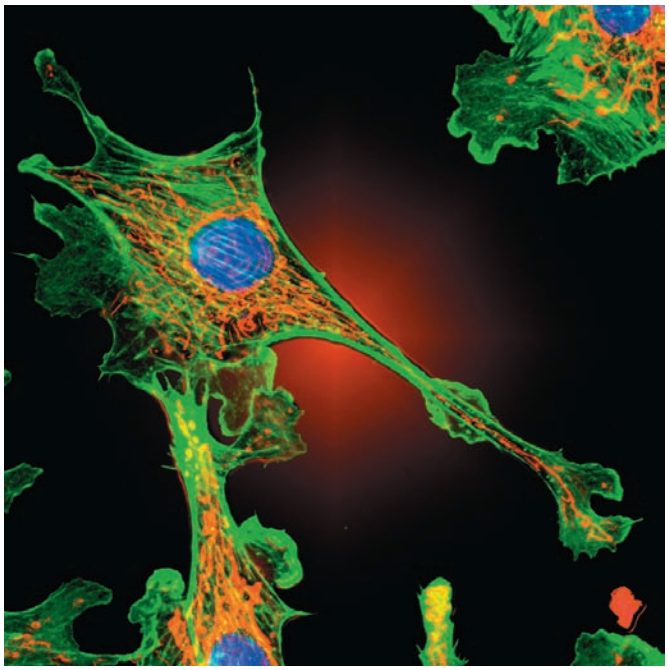
Summary

THE PLANNER

1 The Cell Is Highly Organized and Dynamic 70

- According to the cell theory, all life is composed of cells. Cells come from preexisting cells, they contain hereditary material, and they are composed of similar chemical compounds. Cells have a membrane that separates them from the environment, as well as internal compartments designed to carry out specific functions.
- Cells of plants and animals differ, as do eukaryotes and prokaryotes. Eukaryotes, as shown here, have nuclei and organelles, while prokaryotes do not.

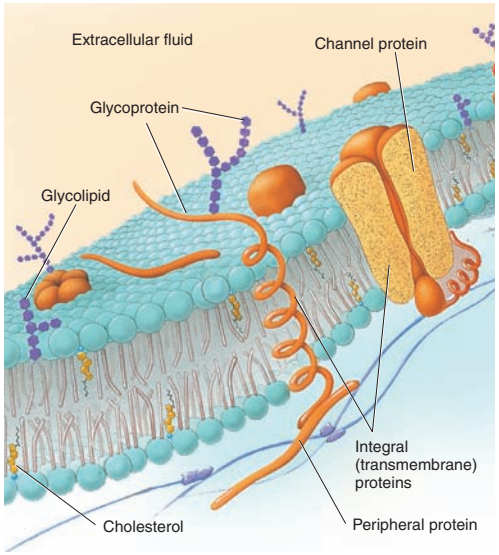
Figure 4.1



2 The Cell Membrane Isolates the Cell 73

- The cell membrane, as shown here, is composed of a phospholipid bilayer, studded with proteins and covered on the surface with the glycocalyx. This liquid membrane is selectively permeable, allowing some substances free access to the cell while excluding others. Passive transport across the membrane requires no energy and includes filtration, diffusion, and facilitated diffusion. Osmosis describes the movement of water across the cell membrane.

Figure 4.2

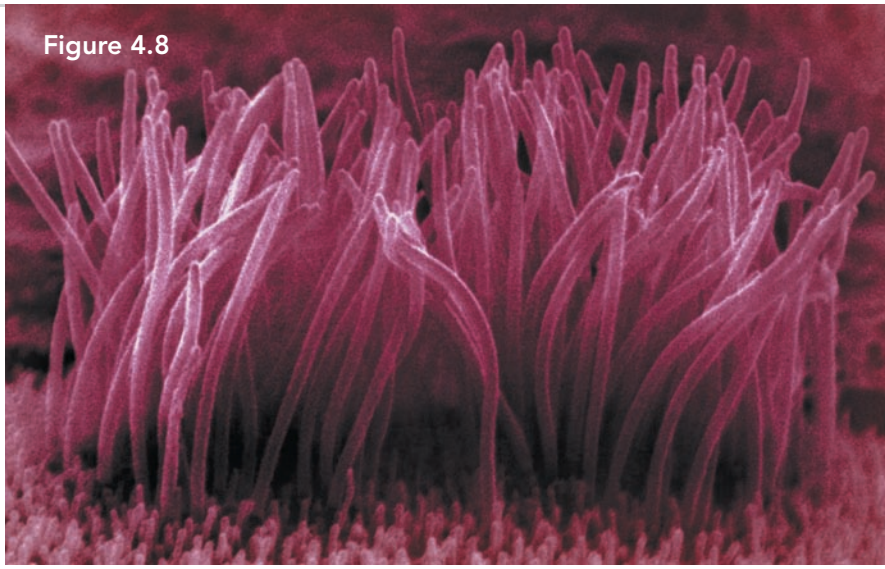


- Solutions can be defined as isotonic, hypotonic, or hypertonic, depending on the concentration of water relative to that in the cell.
- Active transport requires ATP and includes moving substances into the cell (endocytosis) and out of the cell (exocytosis) against their concentration gradients.

3 The Components of a Cell Are Called Organelles 78

- A typical animal cell has the following organelles: nucleus, nucleolus, RER, SER, ribosomes, Golgi complex, lysosomes, centrioles, cytoskeleton, and mitochondria. Cilia, pictured here, are found on cells that must move fluid past them, and sperm carry a flagellum.
- The cell is a dynamic place, where membrane is constantly being created and used. New membrane made at the RER is processed while moving to the Golgi apparatus and then to a transport vesicle destined to leave the cell. When the vesicle fuses with the cell membrane, the new phospholipid bilayer is spliced into place.

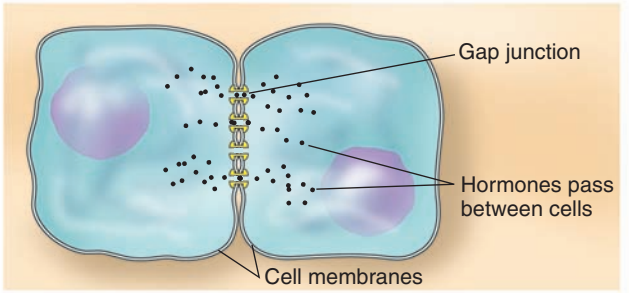
Figure 4.8



4 Cell Communication Is Important to Cellular Success 87

- Cells communicate with one another through chemicals. Hormones carry information long distances in the body, while paracrine hormones convey information locally. Some cells, such as those of the skin or the heart, interact through direct physical contact as well, as shown here.

Figure 4.17



- Cells divide through a communication-laden process called mitosis. They also carry out programmed death, or apoptosis, which also requires cellular communication.

Key Terms

- carotene 71
- cytoskeleton 79
- eukaryotic 72
- glycolipid 73
- glycoprotein 73
- hormone 88
- hydrolytic enzymes 81
- integral protein 75
- isotonic 75
- keratin 71
- melanin 71
- nucleoplasm 83
- organelle 71
- peripheral protein 75
- phospholipids 73
- prokaryotic 72
- saccule 80
- solute 75
- symbiotic 87

Critical and Creative Thinking Questions

1. As a research assistant in a cytology lab, you are handed a stack of photographs from an electron microscope. Each represents a different type of cell. You are asked to identify photos of animal cells that secrete large amounts of protein, do not divide, and include a mechanism for moving their secretions along their surfaces. What organelles would this cell require? Which organelles would you not expect to see?
2. Assume you are now a lead scientist in a cytology lab, studying active transport and "cell eating." You have placed a radioactive marker on a bit of food that was taken into the cell through endocytosis. Trace the pathway this particle would likely take while moving from outside the cell to inside. What organelles will it pass through? Where will it be located within these organelles?
3. CLINICAL CLICK QUESTION
   Cells have an expected life span, just as do people. When Lena and Oscar had their first child, they were looking forward to many years of parenthood. All seemed well for the initial 12 months, with their child growing and developing as expected. By 14 months, however, they noticed some frightening symptoms. Their child's growth rate slowed to below normal. Their baby's face took on a more hawkish, beaked appearance, and eyebrow and eyelash hair began to fall out. The skin on the child's body became loose and aged-looking. They took their child to the doctor for a checkup. What do you think might be causing this increased rate of aging? According to the doctor, the symptoms seem to be due to an inability to repair cells after normal daily wear and tear. Which organelle is responsible for maintaining the instructions for protein production and maintenance repairs? Predict what the effects might be of a mutation that prevents this organelle from remaining intact. Visit http://www.mayoclinic.com/health/progeria/DS00936 or http://www.genome.gov/11007255 to verify your predictions.

What is happening in these pictures?

Poison ivy! This is often an unpleasant interaction with the environment for us. Poison ivy is a common plant in the North American temperate forests that produces an oil to protect it from predation by grazers. As humans occupy the temperate forest environment, we come in contact with the ivy's oil. Our skin cells may be affected by this oil, as well as those cells that line our respiratory tract if the ivy is burned and the smoke inhaled.

NATIONAL GEOGRAPHIC

Think Critically

1. What mechanism is most likely used by this oil to enter the cells: endocytosis, diffusion, or facilitated diffusion?
2. What type of communication system is demonstrated as the irritated cells cause local fluid release and itching?
3. What remedy might work best on this type of environmentally caused rash?

Self-Test

1. Which of the following is NOT a part of the cell theory?
   a. All living things are composed of cells.
   b. Cells cannot arise from preexisting cells.
   c. Chemically all cells are quite similar.
   d. Metabolism occurs within cells.

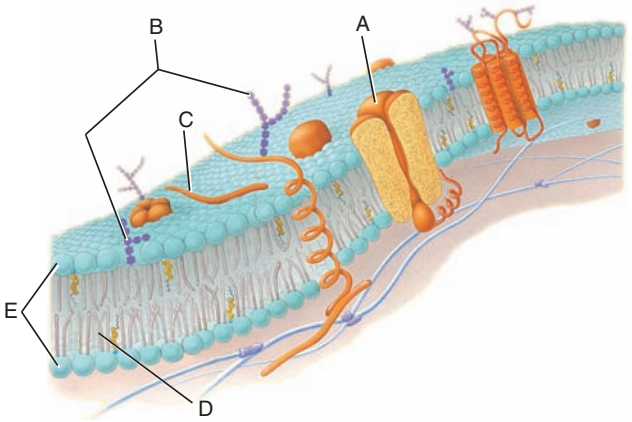
2. An organelle can be defined as _____.
   a. dissolved compounds in the cytosol
   b. a structure within the cytosol that performs at least one vital cellular function
   c. a phospholipid bilayer
   d. the smallest unit of life

3. Within a human cell, it is common to find _____.
   a. cytosol
   b. melanin
   c. ribosomes
   d. All of the above are correct.

4. The cell membrane is made up of phospholipids, which have a hydrophilic phosphate head and a hydrophobic lipid tail.
   a. true b. false

5. Movement across the cell membrane can be passive or active. Which of the following is an example of active transport?
   a. diffusion b. filtration
   c. osmosis d. sodium/potassium ATPase

6. On the figure below, identify the glycocalyx.
   a. A b. B
   c. C d. D



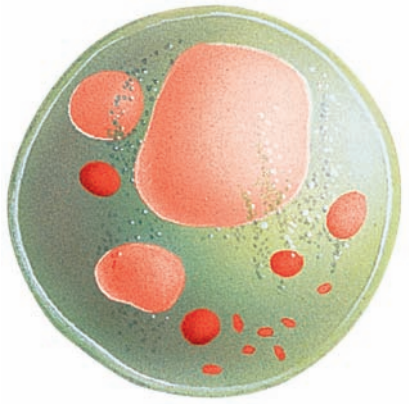
7. Using the same figure, what is the function of structure E?
   a. identifying the cell as self
   b. preventing water entry into the cell (hydrophobic end of the lipid)
   c. allowing proteins to enter the cell
   d. allowing cellular interaction with the aqueous environment of the body

8. Again looking at the same figure, indicate which label identifies the integral proteins.
   a. A
   b. B
   c. C
   d. D
   e. E

9. Putting a cell in a hypotonic solution will result in that cell _____.
   a. shrinking as water passes out of the cell membrane
   b. expanding as water moves into the cell
   c. remaining static, with no net water movement across the membrane
   d. expanding as proteins move into the cell
   e. shrinking as proteins move out of the cell

10. The process of _____ removes secretory products or wastes from a cell.
   a. endocytosis
   b. exocytosis
   c. filtration
   d. cell division

11. What is the function of lysosomes?
   a. ATP production
   b. protein packaging and processing
   c. housing the DNA
   d. digesting worn-out organelles



12. Which organelle is thought to have been a bacterial symbiont that is now permanently incorporated into eukaryotic cells?
   a. mitochondrion
   b. Golgi complex
   c. ribosomes
   d. nucleus

13. The organelles responsible for moving fluid past the surface of a cell are _____.
   a. microvilli
   b. flagella
   c. cilia
   d. RER

14. When a protein is formed, it moves from the ribosome to the RER and then on to the _____, where it is processed for use either in the cell or in the extracellular matrix.
   a. SER
   b. Golgi complex
   c. lysosome
   d. nucleus

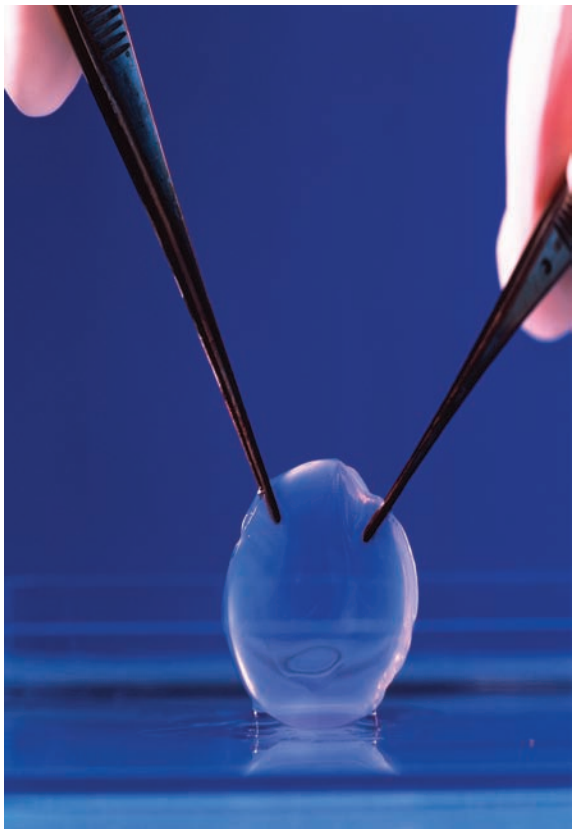
15. Some cells communicate with one another through paracrines, which can be defined as _____.
   a. cell-to-cell contact
   b. long-range hormones
   c. local hormones
   d. gap junctions

THE PLANNER

Review your Chapter Planner on the chapter opener and check off your completed work.

Tissues

Every state in the United States has at least one tissue bank, and some more populated states, such as Texas and California, host more than 20. What is a tissue bank? Who benefits from the macabre holdings within them? A tissue bank is a storage facility for donated human tissues. It may house common donations such as blood, skin, and serum, or more exotic specimens such as breast, lung, or prostate tissue. Perhaps the most unique tissue bank is housed at the Dana-Farber Cancer Institute in Boston, Massachusetts, where samples of brain tumors are kept. All of these tissues, both normal and diseased, are harvested from tissue donors and kept alive using tissue culture methods. Some tissues are used for transplant. For instance, blood, corneas, and heart valves are used as replacement tissues for accident victims. Bone and soft tissues are used to reconstruct tissue for broken bones or torn ligaments and tendons. Still others are maintained strictly for research purposes. What better way to determine whether a drug regime will be effective against a cancerous tumor than to directly test it in the lab? Another value of tissue bank specimens lies in research. Comparing normal to diseased tissue in a laboratory setting provides clues to disease prevention that are not evident in whole animal studies. Currently, skeletomuscular tissues are being used to investigate osteoporosis, muscular dystrophy, multiple sclerosis, and arthritis. Donated human lenses are being used to discover the causes and treatments of cataracts, and donated normal and diseased nervous tissue is the cornerstone of Alzheimer's and Parkinson's disease research.



CHAPTER OUTLINE

Cells Are the Building Blocks of Tissues 96

- Epithelial Tissue Is at the Surface
- Connective Tissue Keeps It Together
- Muscular Tissue Moves Us
- Nervous Tissue Is the Body's Phone and Computer System

Organization Increases with Organs, Organ Systems, and the Organism 107

- There Are 11 Organ Systems in the Human Body
- The Goal of the Organism Is to Maintain Homeostasis

Scientists Use a Road Map to the Human Body 111

- The Body Has Two Large Cavities

CHAPTER PLANNER

- ❑ Study the picture and read the opening story.
- ❑ Scan the Learning Objectives in each section:
  p. 96 ❑ p. 107 ❑ p. 111 ❑
- ❑ Read the text and study all figures and visuals. Answer any questions.

Analyze key features

- ❑ What a Scientist Sees, p. 100
- ❑ Health, Wellness, and Disease, p. 103
- ❑ I Wonder..., p. 105
- ❑ Ethics and Issues, p. 110
- ❑ Biological InSight, p. 113
- ❑ Stop: Answer the Concept Checks before you go on:
  p. 106 ❑ p. 110 ❑ p. 113 ❑

End of chapter

- ❑ Review the Summary and Key Terms.
- ❑ Answer the Critical and Creative Thinking Questions.
- ❑ Answer What is happening in this picture?
- ❑ Answer the Self-Test Questions.

5.1 Cells Are the Building Blocks of Tissues

LEARNING OBJECTIVES

1. **List** the four tissue types in the human body.
2. **Describe** the function of each tissue type, explaining its unique characteristics.
3. **Outline** the various types of epithelial, connective, and muscular tissue.

Efficiency in life processes is key to organisms' ability to adapt to a changing environment. Organelles allow cells to perform specialized functions efficiently, leading to the formation of groups of cooperative cells forming colonies. These colonies could specialize further, increasing their efficiency, by forming tissues. A tissue is a group of similar cells and extracellular substance that have combined to perform a single function. The human body has four tissue types:

- **Epithelial** tissue covers the body, lines all cavities, and composes the glands.
- **Connective** tissue connects the structures of the body, providing structural support and holding organs together. Stretchy and strong, connective tissue maintains the body's integrity.
- **Muscular** tissue provides movement and heat.
- **Nervous** tissue responds to the environment by detecting, processing, and coordinating information.

Epithelial Tissue Is at the Surface

Epithelial tissue (or simply epithelium) is composed of cells laid together in sheets—strong cell-to-cell attachments hold the cells together. One side of these cells is oriented toward the surface of the tissue—either the body cavity or external environment—and may have cilia or **microvilli**. The other surface is joined to deeper connective tissue at the **basement membrane**. This basement layer, an acellular membrane, is composed of a collection of polysaccharides and proteins that help to cement the epithelial tissue to the underlying structures.

microvilli Small hair-like folds of the cell membrane that increase the cell's surface area for absorption.

Epithelium is little more than cells tightly connected, one to the next. It has neither blood vessels nor any extracellular substances between the cells. Epithelial types are identified by both the number of cell layers and the shape of the cells in the upper layer. In total there are eight basic types of epithelium: six identified by both the number of cells and their shape, and two (transitional and pseudostratified) named for the type of cell found in them (see Figure 5.1).

Simple epithelium has one layer of cells and usually functions as a diffusion or absorption membrane. The lining of your blood vessels and the respiratory membranes of your lungs are simple epithelium. **Stratified** epithelium has many layers of cells and is designed for protection. Examples are found in the outer layer of your skin and the ducts of your salivary glands.

Epithelial cells can be flattened, cube-like, or columnar. Each shape mirrors the function of the tissue. Flattened cells, reminiscent of fried eggs, are called **squamous** cells. Squamous epithelium is thin enough to form a membrane through which compounds can move via diffusion. **Cuboidal** and **columnar** epithelia are plumper and usually compose mucous membranes in which the epithelial cells secrete mucus and other compounds.

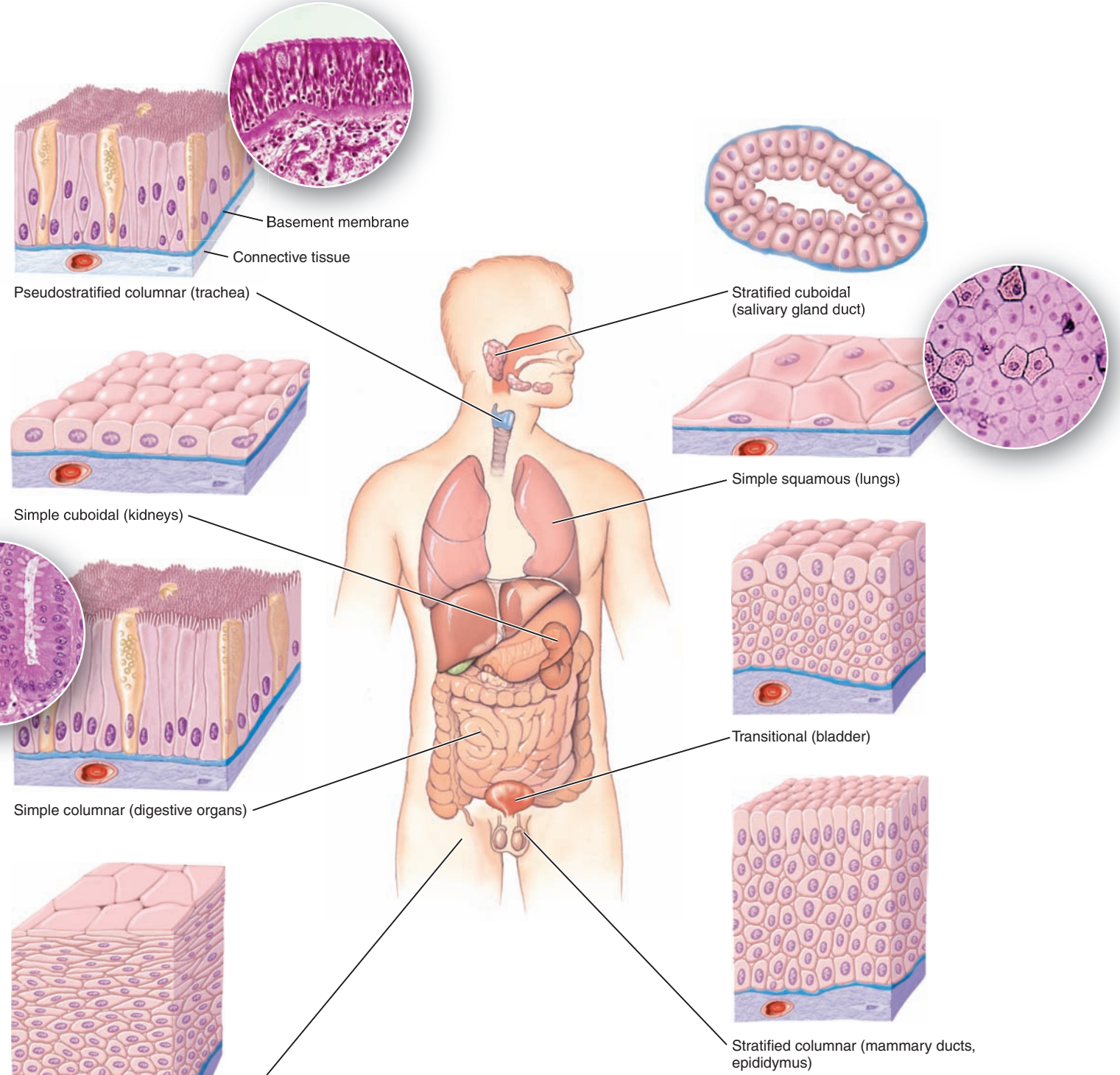
Glands are composed of epithelial tissue and classified by how their secretions are released. Glands that secrete into ducts are **exocrine** glands. Salivary glands and sweat glands are exocrine glands. Each one secretes its products into a duct that directs the secretion to the surface of the gland.

Endocrine glands have no ducts. Instead, they secrete directly into the extracellular fluid surrounding the gland. Endocrine glands secrete hormones that are then picked up by the bloodstream and carried throughout the body. The adrenal, thyroid, and pituitary glands are all endocrine glands.

Connective Tissue Keeps It Together

As the name implies, connective tissue connects bodily structures. It binds, supports, and anchors the body and is the most abundant type of tissue in the body. As you can imagine, problems with connective tissue therefore can be life threatening. Connective tissue is composed of cells suspended in a noncellular **matrix**. The matrix, or "ground substance," is secreted by the connective tissue cells, and it determines the characteristics of the connective tissue.

Epithelial tissue • Figure 5.1

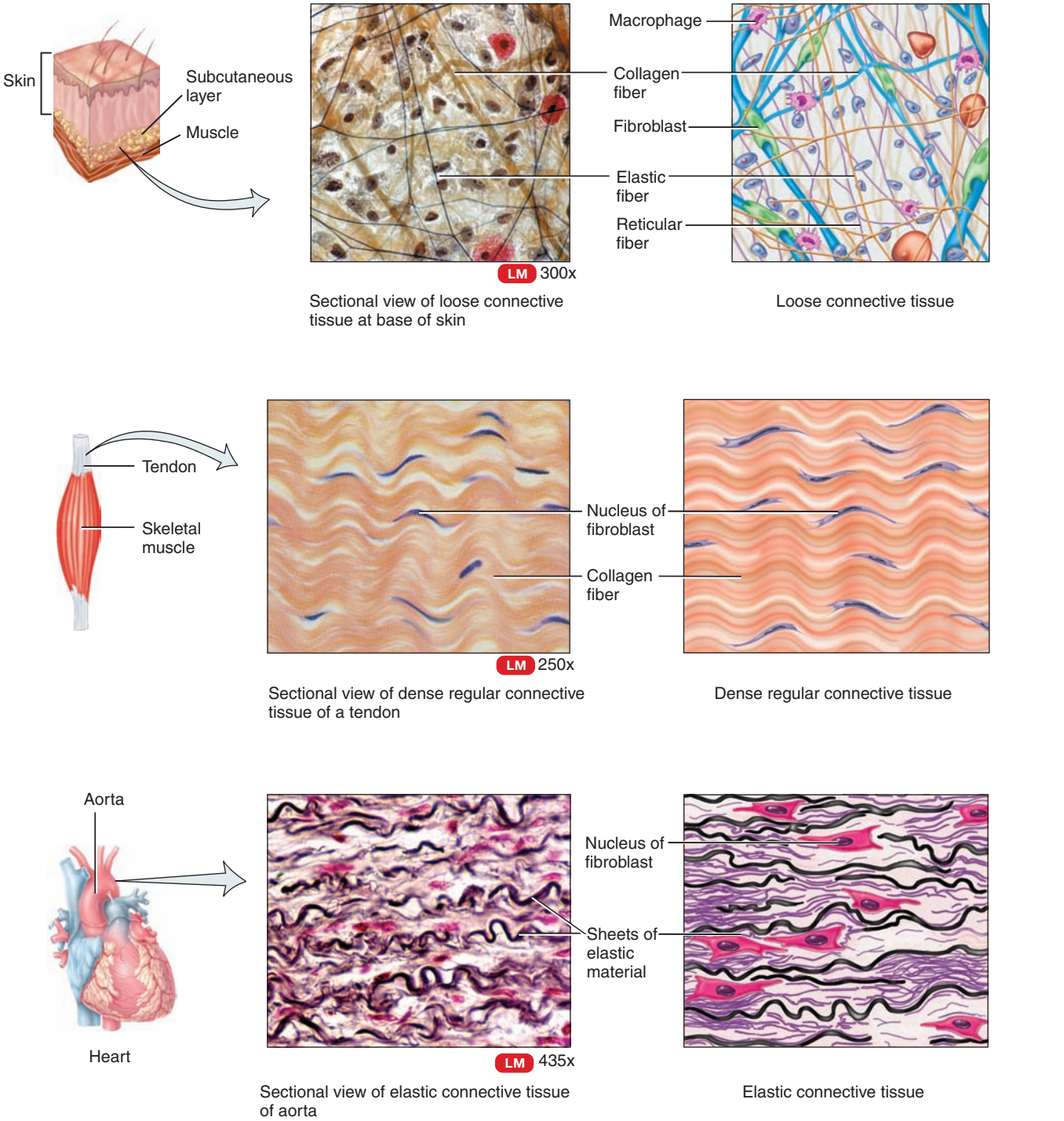


Cell shapes and the arrangement of layers are the basis for classifying epithelial tissues. The shape of the topmost layer of cells determines the name of stratified epithelium, because this layer is not deformed by those above it. Layers of flattened cells that look like "piles of tiles" are classified as stratified squamous epithelium, whereas layers of plump cells are classified as stratified cuboidal epithelium. Pseudostratified epithelium appears to be composed of layers of cells, but in fact each and every one touches the basement membrane. Transitional epithelium is found lining organs that expand, such as the urinary bladder. When the bladder is empty, transitional epithelium appears stratified, but when the bladder fills, the transitional epithelium is stretched over the increased surface area and appears as a single layer.

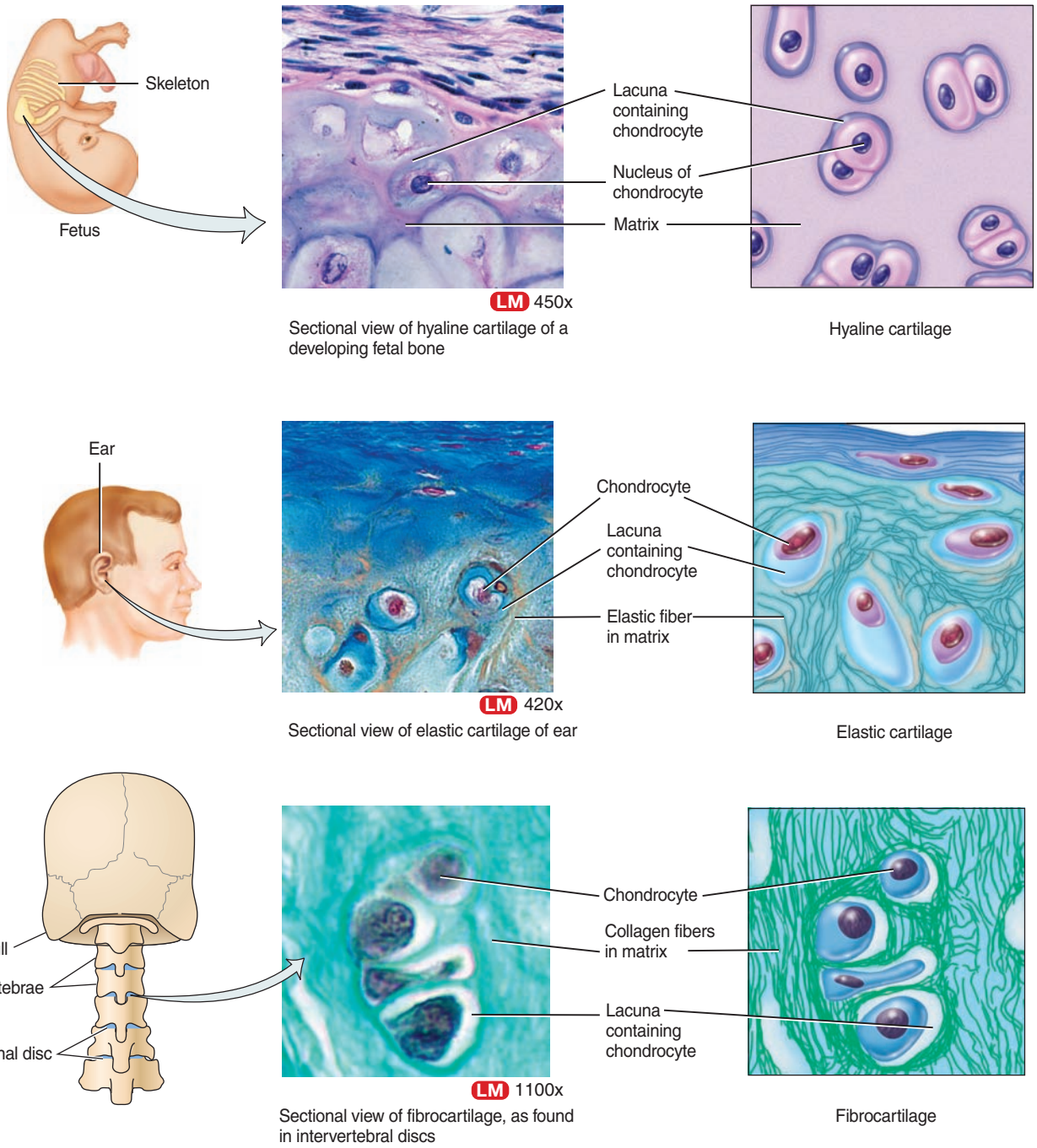
The matrix can be liquid, gel-like, or solid, depending on the cells. The ground substance of all connective tissue contains fibers of **collagen** (for strength) and **elastin** (for flexibility, stretch, and recoil). Collagen is one of the main components of all connective tissue and consequently is the most abundant protein in the animal kingdom.

The nature of the ground substance leads us to classify connective tissue as either **soft connective tissue** or **specialized connective tissue**. Soft connective tissue examples include parts of our skin, tendons, and blood vessels, as shown in **Figure 5.2**. Cartilage, bone, blood, and lymph are types of specialized connective tissues.

Soft connective tissues: loose, dense, and elastic • Figure 5.2



Cartilage • Figure 5.3



Soft connective tissue has a matrix composed of semifluid substance. It also has fibroblasts that secrete fibers, and white blood cells that fight infection. The fibers of the matrix can be either loosely arranged or densely packed together. See Figure 5.2 for details. Loose connective tissue is sometimes called areolar connective tissue. Dense connective tissue includes the dense irregular tissue of the dermis of the skin, where the collagen fibers are arranged in a network, and the dense regular tissue of tendons, where the collagen fibers are aligned to resist tearing. Elastic connective tissue is made up of freely branching elastic fibers with fibroblasts in the spaces between the fibers.

Cartilage cushions and joins. Cartilage is a unique connective tissue because it is **avascular**—other types of connective tissue all have rich blood supplies (see **Figure 5.3**). **Chondrocytes**, the cartilaginous

avascular Without blood vessels.

NATIONAL GEOGRAPHIC

WHAT A SCIENTIST SEES

THE PLANNER

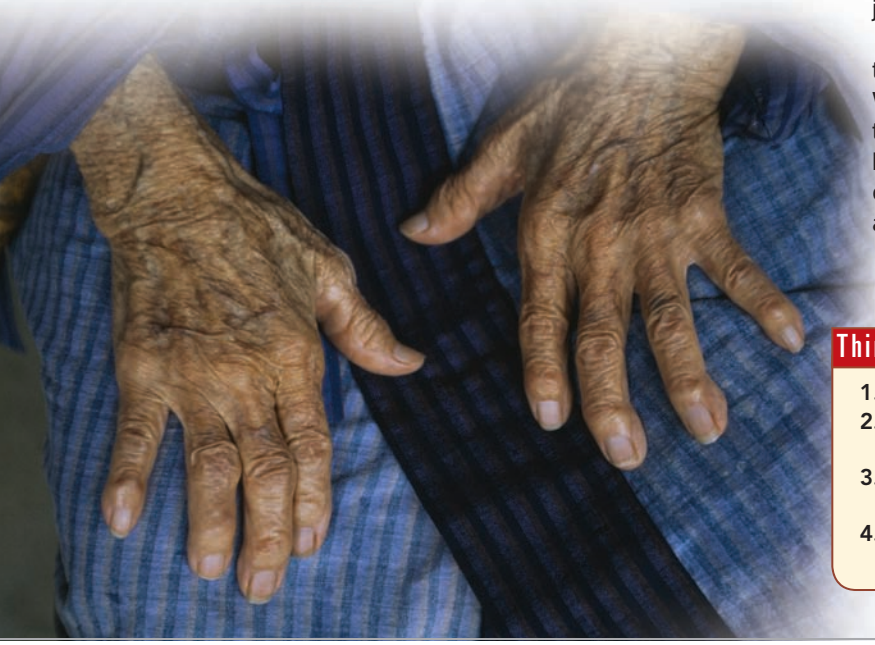
Arthritis Attacks

Arthritis is a general term for degradation of the joints, with a variety of causes. Rheumatoid arthritis results from an autoimmune attack on the joint. Osteoarthritis results from various sorts of wear and tear. Only one type of arthritis, the one that results from an infection, can be cured (using antibiotics). Other forms must be managed to reduce pain and improve quality of life.

Rheumatoid arthritis is an inflammation of the synovium, which lines the joints. The disease can seriously deform the hands, but it often affects joints throughout the body. Rheumatoid arthritis is two or three times as common among women, indicating that women are genetically more susceptible to this type of autoimmune attack than are men. A proper diagnosis must precede treatment, as doctors want to rule out other diseases that can affect the joints, such as lupus or fibromyalgia.

A variety of new medicines called biological response modifiers may limit inflammation in rheumatoid arthritis by interfering with an immune protein called tumor necrosis factor. Alternatively, surgeons may fuse bones to prevent movement at the affected joint, or may replace the joint with a metal joint.

Arthritis research continues. Scientists want to understand the role of genetics or a prior infection in triggering joint damage. What exactly is going wrong with the immune system and cells in the joint? Because joint damage can be permanent, researchers hope to stop the damage at an early stage. This explains the interest in "biological markers"—unique compounds or proteins that are associated with arthritic processes.



Think Critically

1. What visual clues can be used when initially diagnosing arthritis?
2. What specific underlying problem might be causing these visual anomalies?
3. What type of tissue do you suppose is affected by rheumatoid arthritis?
4. What is the synovial membrane, or any membrane in the body, composed of?

cells, secrete a gel-like matrix that eventually surrounds and imprisons them, segregating them from direct contact with one another or any nutrient supply. Cartilage heals slowly because nutrients must diffuse through the matrix to the chondrocytes; nutrients cannot reach the cells directly via the bloodstream. Each chondrocyte resides in a small "lake" within the matrix called a lacuna. The fluid bathing the cell in this lacuna diffuses through the matrix to and from the blood supply. This indirect route is far slower than bringing the fluid directly to the cells and is the reason cartilage is so slow to repair itself. Osteoarthritis is a serious disease of the joints, targeting the cartilage found within them. It is difficult to treat, in part because the cartilage is avascular and therefore does not respond quickly to medications (see *What a Scientist Sees: Arthritis Attacks*).

The most common type of cartilage is **hyaline cartilage**. The matrix of hyaline cartilage contains many collagen fibers and looks crystal blue in living tissue. Hyaline cartilage covers the ends of bones, allowing them to slide against one another without damage. It is also found in your nose and **trachea**. During development, most of your skeleton was modeled in hyaline cartilage, which then ossified—that is, turned to bone.

trachea The main trunk of the respiratory tree.
epiglottis Large, leaf-shaped piece of cartilage lying over the top of the larynx.

A second kind of cartilage is **elastic cartilage**, which contains many elastic fibers in the matrix. Elastic cartilage allows the outer ear to bend and then return to its original shape. The **epiglottis** that prevents food and liquid from entering your respiratory tract also contains elastic cartilage.

When you swallow, the epiglottis bends to cover the opening of the trachea. Afterward, the epiglottis snaps back to its original position, allowing air to flow through the windpipe.

The third kind of cartilage is **fibrocartilage**. The matrix of fibrocartilage is packed with collagen fibers, so it is found where extra strength is needed. Cushions in your knee joints and the disks between the vertebrae are made of fibrocartilage.

Bone is similar to steel-reinforced concrete. Bone is a hard, mineralized tissue found in the skeleton, which is a defining characteristic of vertebrates—as shown in Figure 5.4. Bone cells secrete an **osteoid** substance that eventually hardens and surrounds the cells in an **ossified** matrix. This "osteoid ground substance" includes proteins, water, calcium, and phosphorous salts. Once the matrix ossifies, the cells remain in contact with one another through small channels called **canaliculi**. Like other connective tissues, bone has collagen fibers in the matrix for flexible support. Young bone has a higher percentage of collagen fibers than older bone, accounting for the greater flexibility of bones in infants and young people. Where an adult's bone will snap under excessive force, a young child's bone will bend. The convex surface may fray, like a bent green stick, but the bone does not break.

osteoid Stage of bone matrix before it calcifies.

Blood and lymph communicate with the entire body. Blood and lymph are considered fluid connective tissues because their matrix is not a solid. Blood is composed of specialized cells that are carried in the fluid matrix, or **plasma** (see Figure 5.5 on the next page). The main function of blood is to transport nutrients, gases, hormones, and wastes. Chapter 12 devotes an entire section to blood.

plasma The clear, yellowish fluid portion of blood.

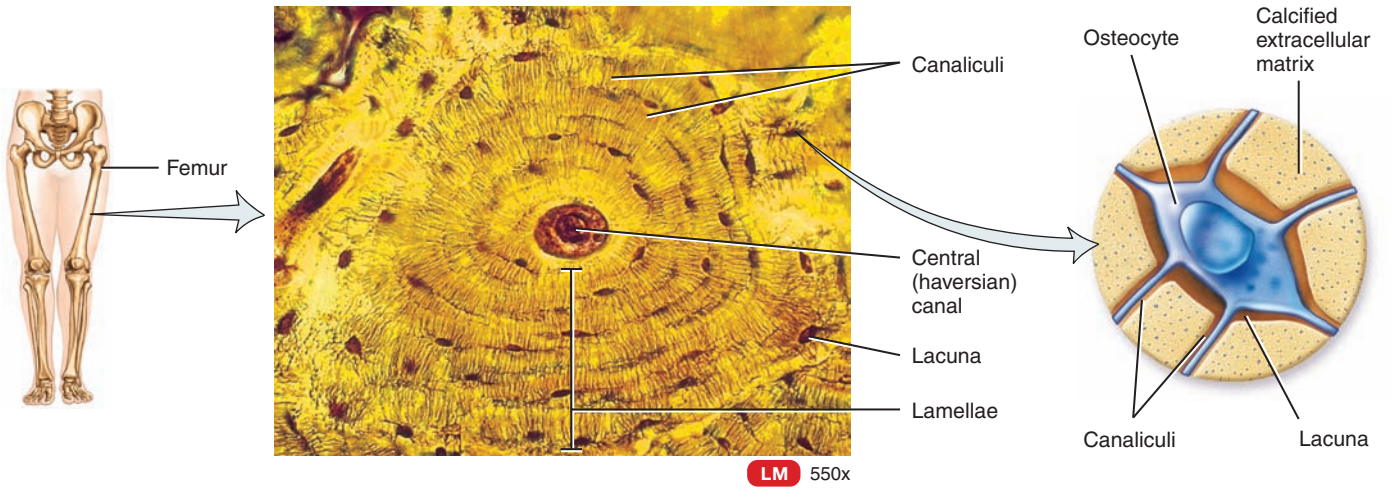
Lymph is another fluid connective tissue. It is derived from the **interstitial fluid** that bathes the cells and is collected in the lymphatic vessels. Like blood, lymph includes cells as well as proteins and other compounds in its fluid matrix. Chapter 10 deals with lymph in greater detail.

interstitial fluid Fluid that fills the spaces between cells of tissues.

Even fat has a job to do. Adipose tissue contains fat cells—cells that are specialized for lipid storage. Unlike other connective tissues, adipose tissue does not have an extensive extracellular matrix. Its matrix is a soft network of fibers holding the cell together and binding it to

Compact bone • Figure 5.4

Bone consists of a hard matrix surrounding living cells. Bone has both a blood supply and a nerve supply running through it. The matrix of compact bone is found in long cylinders called osteons or Haversian systems. Lighter, spongy bone has less structure and is formed in struts and supports rather than a solid mass.

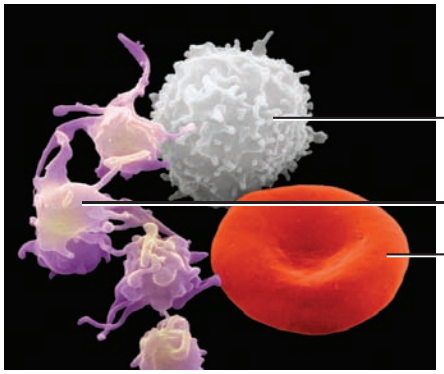


Sectional view of an osteon (haversian system) of femur (thigh bone)

Detail of an osteocyte

Blood components • Figure 5.5

Blood is composed of specialized cells—red and white cells and platelets—carried in a fluid called plasma.



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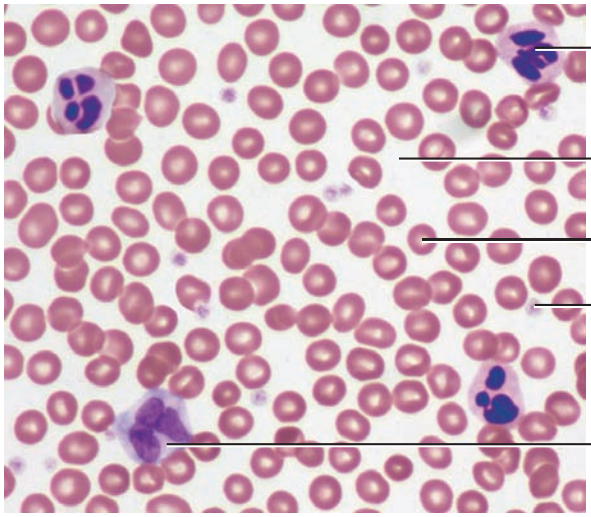


LM 400x

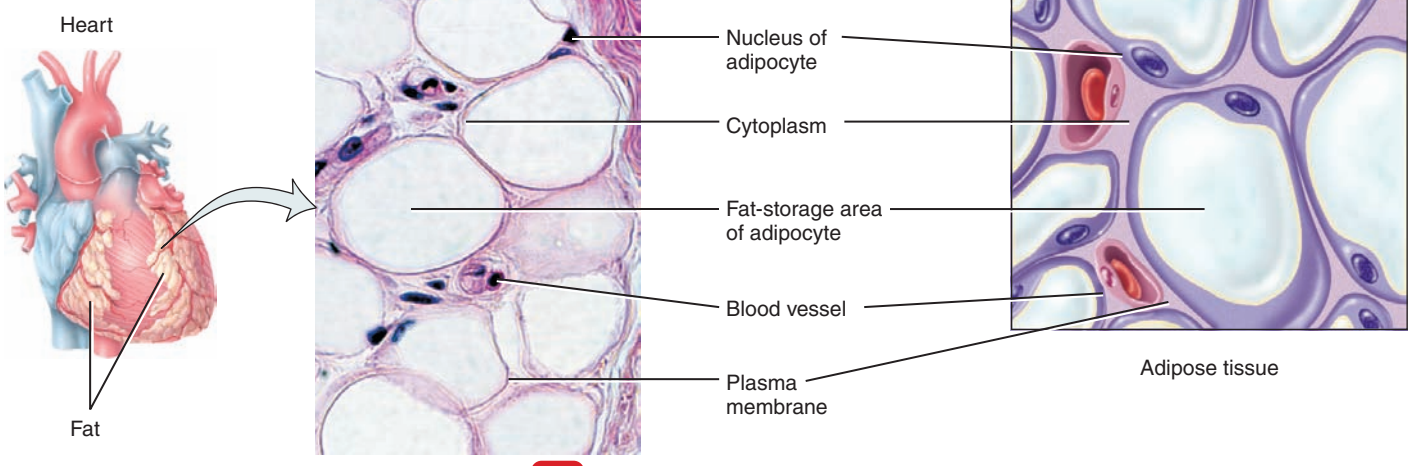
surrounding tissues. Adipose structure is shown in **Figure 5.6**. **Cellulite** "bumps" on the skin indicate where the adipose matrix is connected to the skin. The adipose cells within the fibrous matrix can expand with the swelling of the fat droplets they contain, whereas the matrix fibers cannot stretch as far. The different stretching capacities of these two components of adipose tissue form dimples on the skin. Cellulite is a normal function of fat deposition and storage. It is not an inherently evil tissue that must be removed from the body, despite what you may have read in the supermarket tabloids. Even newborns have cellulite! See *Health, Wellness, and Disease: Is Liposuction the Easy Way Out?* to read more on this topic.

Muscular Tissue Moves Us

The function of muscular tissue is to contract. The cells get shorter, generating force and often movement. The three types of muscular tissue are **skeletal muscle**, **smooth muscle**, and **cardiac muscle**. Skeletal muscle tissue is

Adipose tissue • Figure 5.6

The nucleus and cytoplasm in adipocytes play second fiddle to the main action: the huge droplet of stored fat.



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Sectional view of adipose tissue showing adipocytes of white fat

HEALTH, WELLNESS, AND DISEASE

Is Liposuction the Easy Way Out?

Sometimes dieting and exercise just are not enough. Deposits of concentrated fat can remain even after fastidious caloric monitoring and exercise. When fat cells just will not shrink, liposuction may be recommended. Liposuction is a surgical procedure that removes adipocytes from problem areas. The idea is that if the cells are not present, they cannot swell with stored fats. Of course, this does not mean that the patient will not be able to gain weight. The only guarantee is that the patient will not experience fat deposits again where the adipose cells have been removed. New adipocytes will not replace those that are gone, but remaining adipocytes can swell and effectively negate any weight loss or cosmetic benefits of the procedure.

Liposuction can be an outpatient procedure or it may require an overnight stay, depending on the amount of tissue removed. Smaller removals usually require only a local anesthesia, while a more extensive removal will require general anesthesia. Once anesthetized, a small incision is made. The surgeon inserts a small metal cannula and either vacuums out large areas of adipose with a suction pump or removes smaller deposits with a syringe. If large deposits are being removed, the surgeon may opt to inject the site with saline, a mild painkiller, and epinephrine. The epinephrine constricts capillaries, reducing blood loss and bruising. Even with small removals, however, bruising and swelling are expected side effects. Adipose is a highly vascularized tissue, and will bleed when disrupted. The adipose that is removed lies between the skin and muscles. In some cases, elastic cuffs are necessary to hold the skin in place until healing begins.

highly organized, with the cells lying parallel to each other, much like a cable. When stimulated, groups of muscle cells contract in unison (see **Figure 5.7** on the next page).

Skeletal muscle is the tissue that makes up the muscles. Skeletal muscle moves your limbs and stabilizes your trunk, including your **biceps brachii** and **rectus abdominus**. This tissue is composed of long, multinucleate cells with visible **striations**. The cells of skeletal muscle extend the length of the muscle and are arranged in parallel groups called **fascicles**. Skeletal muscle is described in full detail in Chapter 6. Because you consciously control muscle contractions, skeletal muscle is called voluntary muscle.

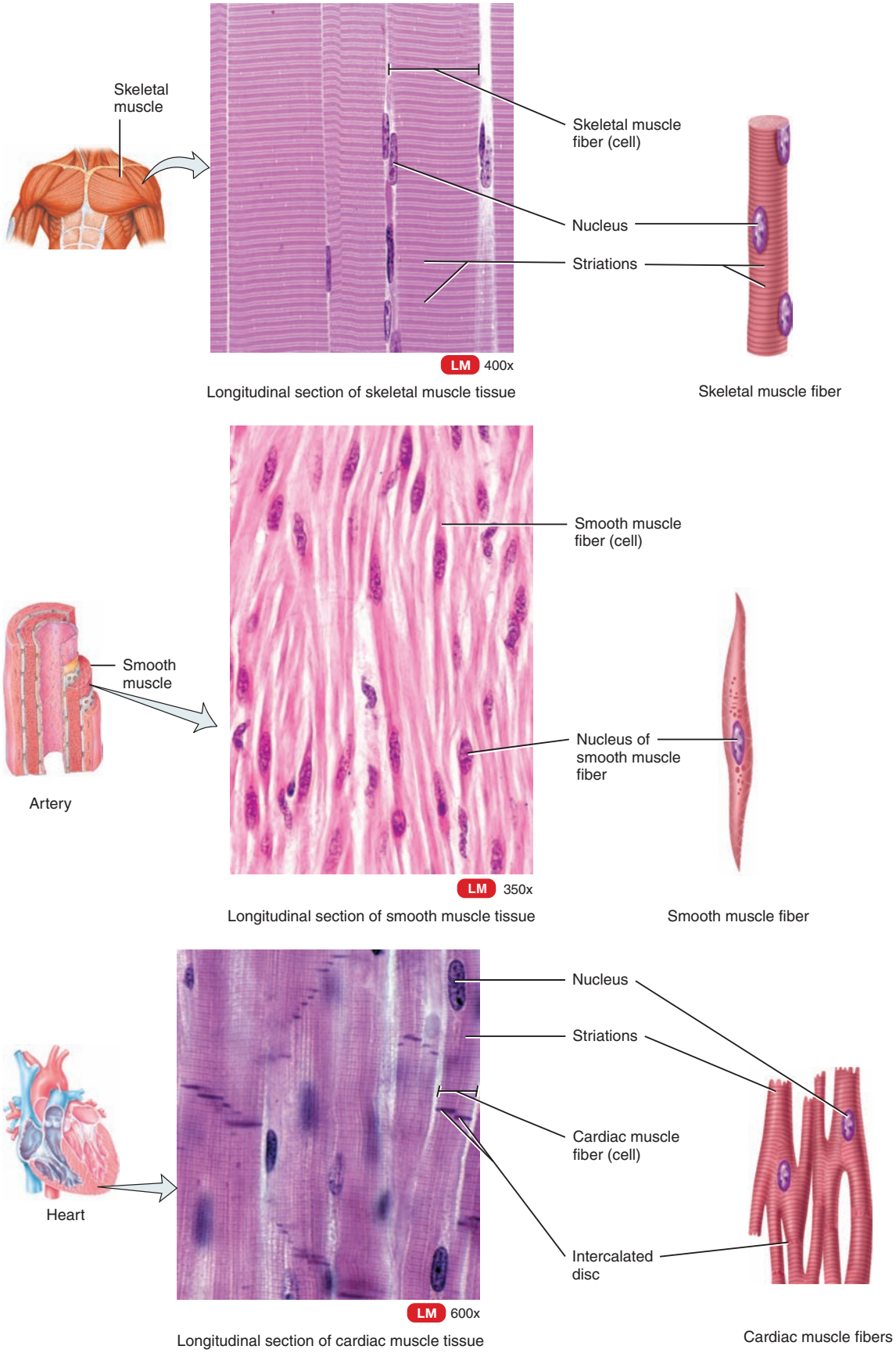
biceps brachii The anterior muscle of the upper arm.

rectus abdominus "Six-pack" muscles that stabilize the trunk.

striations A series of parallel lines.

Smooth muscle lines hollow organs, such as the blood vessels and the digestive tract. Smooth muscle cells are short, cylindrical cells that taper at both ends and have only one nucleus. They are not striated and are not under voluntary control. This last attribute is helpful. Wouldn't it be nerve-wracking to have to consciously manage the diameter of your blood vessels to maintain blood pressure, or to consciously create the rhythmic constrictions that the digestive tract uses to move food during digestion?

Comparison of three types of muscle tissue • Figure 5.7



THE PLANNER

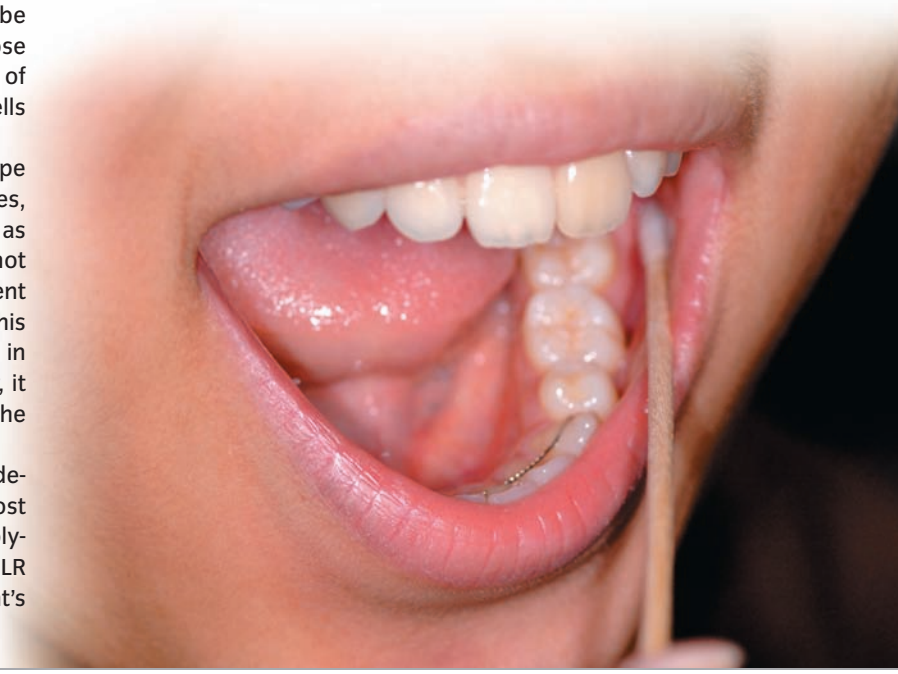
I WONDER...

What Is Tissue Typing?

If there are only four types of tissue in the human body, how difficult can it be to type human tissue? In fact, the term *typing* means more than simply identifying the category of tissue being discussed. It even goes beyond identifying the subcategory, such as areolar connective tissue or cardiac muscle. The cell membranes of various types of tissue exhibit subtle differences that must be taken into consideration in determining what type of tissue those cells represent. This determination requires a complex process of testing and analysis usually begun by removing a sample of cells using a simple cheek swab.

The most commonly used marker for determining tissue type is HLA, or human lymphocyte antigens. The body's lymphocytes, or immune cells, use HLA marker antigens to recognize a cell as belonging to the body; if it does belong, the lymphocytes will not attack it. If they encounter "foreign" cells that carry a different form of HLA, they will attack and destroy those cells. Usually this is a good thing, because "foreign" cells should not be present in the body. For patients undergoing organ transplants, however, it is imperative that the HLA antigens on the new organ match the patient's HLA as closely as possible.

A series of laboratory tests can be performed that will determine what markers the patient's cells carry. Two of the most common tests are a mixed lymphocyte reaction (MLR) and a polymerase chain reaction (PCR). (PCR is discussed in Chapter 20.) MLR combines samples of potential donor tissue with the recipient's blood. If there is an increase in lymphocytes during the testing procedure, it is assumed that they are responding to a "foreign invader" and launching an attack. This would be fatal in a transplant, because the patient's immune cells could attack the new organ and destroy it.



Cardiac (heart) muscle has short, branched, striated cells, with one nucleus at the center of each cell. Specialized communication junctions called intercalated discs facilitate the heartbeat by transmitting the signal to contract. Intercalated discs are gap junctions where the closely knit cell membranes help to spread the contraction impulse while also binding the cells together. Cardiac muscle will be described in more detail in Chapter 12. Heart tissue, along with smooth muscle, epithelium, and connective tissue, can all be transplanted. To understand what this entails, see *I Wonder… What Is Tissue Typing?*

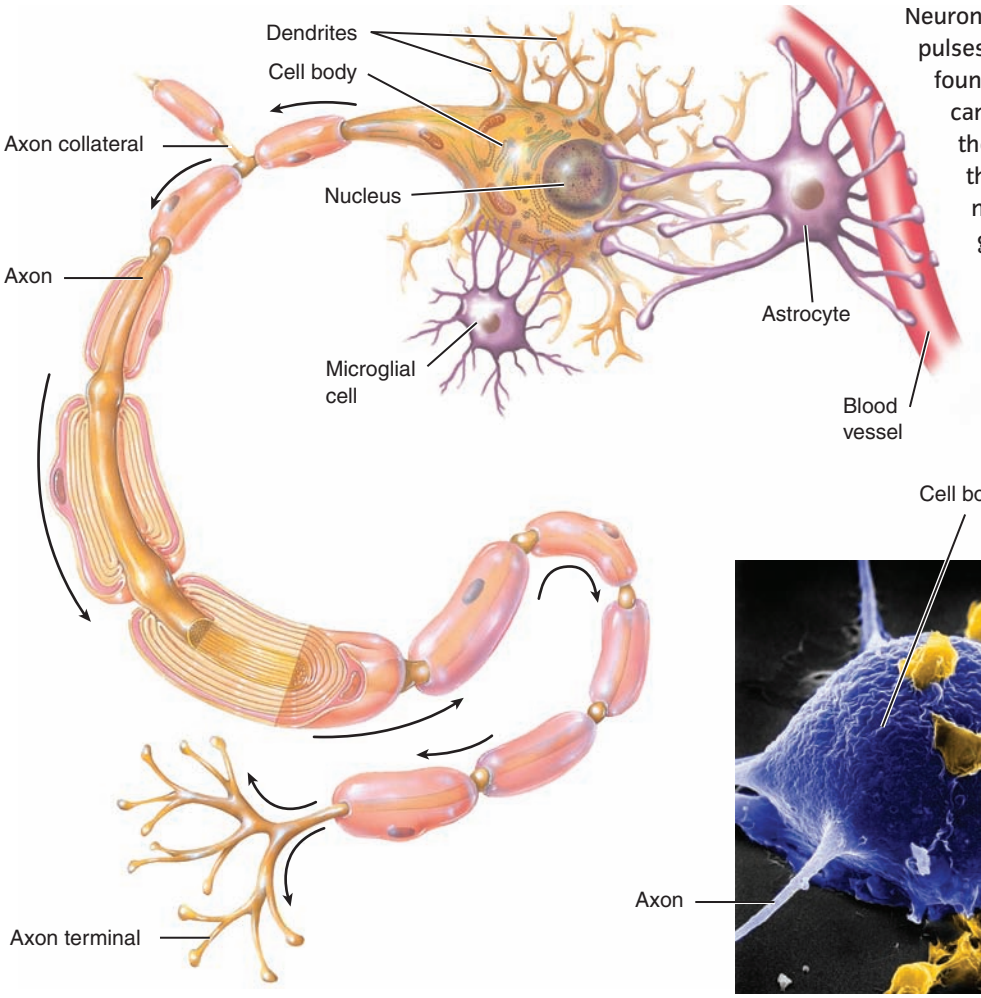
Nervous Tissue Is the Body's Phone and Computer System

Nervous tissue, the final type of tissue in the human body, is "irritable," which means it responds to changes in the environment. Nervous tissue contains two categories of cells—**neurons** and **neuroglia**—as seen in Figure 5.8 on the next page.

Neuroglia are the supporting cells of nervous tissue (*glia* means "glue"). It was once thought that these cells merely held the neurons together. Now we know that the various neuroglial cells have specific supporting roles. Neuroglia do not send or receive electrical impulses. Instead, they improve nutrient flow to the neurons, provide physical support, remove debris, and provide electrical insulation.

Nerves are clusters of neurons and their projections, sheathed in connective tissue. Because nerves exist in the body's periphery, they are part of the **peripheral nervous system**. Sensory nerves conduct sensory messages from the body's **sensory organs** to the spinal cord, which routes the information to the brain. Motor nerves carry impulses that cause muscular movement or glandular secretion

Neurons and neuroglia • Figure 5.8



Neurons are the cells that carry electrical impulses. They can be extremely short, like those found within the spinal cord and brain, or they can be longer than 125 centimeters, like those that extend from the spinal cord to the end of the great toe. The cell body of a neuron has long, slender projections. One group of projections, called **dendrites**, receives impulses from other neurons, bringing the information to the cell body. The other projection, called the **axon**, transmits impulses from the cell body to other cells. Individual neurons may have many dendrites, but each can have only one axon.

from the spinal cord to the muscles and glands. The brain and spinal cord contain neurons that receive and integrate information and stimulate motor neurons to fire. These information-processing neurons occur in the central axis of the body, so they comprise the **central nervous system**. The breakdown of the nervous system and the histology of nervous tissue are covered extensively in Chapter 7.

As you have seen, tissues are composed of cells working together to perform a single function. In most cases, the cells divide and reproduce only enough to perform the function of the tissue. Sometimes, though, the integrity of the tissue can be damaged through uncontrolled cellular growth. When cancer strikes a tissue, not only can it cause malfunctioning of that tissue, but it can also spread to other areas of the body. Cancer is a disease of both cells and tissues that is capable of destroying the entire body. Newer forms of cancer therapy reflect the fact that cancer is a general term for many different diseases caused by various problems with cells and the intercellular signaling system in tissues. In Chapter 11, we will revisit this subject in depth.

CONCEPT CHECK

1. **What** are the four tissue types in the human body?
2. **What** are the primary functions of the four tissue types?
3. **How** are the functions of the different types of epithelial, connective, and muscle tissue related to their structures?

5.2 Organization Increases with Organs, Organ Systems, and the Organism

LEARNING OBJECTIVES

1. **Explore** how organisms display the hierarchy of life.
2. **Outline** the role organ systems play in maintaining homeostasis.

Recall that one characteristic of life is a high degree of organization. A layered organization, or hierarchy, is visible in all life-forms:

- Atom
- Molecule
- Organelle
- Cell
- Tissue
- Organ
- Organ system
- Organism

The four main types of tissues we have covered—epithelial, connective, muscular, and nervous—join together in specific proportions and patterns to form organs, such as the heart, brain, and stomach. Each organ has a specific, specialized, and vital function. Organs that interact to perform a specific task comprise an organ system. For example, the heart and the blood vessels together make up the cardiovascular system. Although each organ system has one specialized function, the continuity of life requires that these systems be integrated into a whole, cohesive unit. The ultimate level of organization, then, is the **organism**. In human biology, the human being is the pinnacle of organization, although humans are also part of a larger social and ecological framework, as discussed later in this text. You are composed of cells cooperating in tissues, which are in turn positioned together to efficiently carry out an organ's processes. Organs then work together to perform a larger function, such as cleansing the blood, comprising an organ system.

There Are 11 Organ Systems in the Human Body

Each of the organ systems in the human body will be discussed in this text: integumentary (protecting and covering), skeletal (supporting), muscular (mobilizing and providing heat), nervous (sensing and responding), cardiovascular (transporting fluids and oxygen), respiratory (regulating gas exchange), urinary (maintaining fluid balance), endocrine (regulating sequential growth and development), digestive (obtaining nutrients), lymphatic (providing immunity), and reproductive systems (continuing the species). See **Figure 5.9** on the next page.

Ten of these systems help maintain homeostasis, while the reproductive system maintains the human population. All 11 organ systems, integrated and working together, maintain life as you know it. When something goes wrong with an organ, the system as well as the entire organism suffers. Replacement organs are usually in short supply, necessitating the creation of new medical solutions. Growing organs in the lab sounds like the plot of a next-generation Frankenstein story. There is a basis of truth to it, however. Researchers at Wake Forest University have been able to grow new, functional urinary bladders. Of course, this opens the possibility of a brave new world where "organ farms" create a new and possibly competitive market for human organs. See *Ethics and Issues: Organ Transplants* on who gets an organ transplant now.

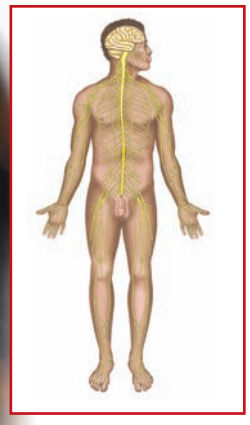
The Goal of the Organism Is to Maintain Homeostasis

You put food into the digestive tract, requiring water and energy to digest it into nutrients, which are consumed during movement and metabolic activity. You lose fluids through sweating, breathing, and urinating. You alter your dissolved gas concentrations with every breath. Every muscular contraction changes your blood chemistry and internal temperature. Each subtle change in body chemistry must be corrected in order to maintain homeostasis. Alterations in one system affect the functioning of all other systems; metabolism in the muscles requires oxygen, which is delivered through the respiratory and cardiovascular systems. You are a finely balanced machine, and every mechanical action, every chemical reaction, requires that balance be restored. Negative feedback loops keep your vital statistics in acceptable ranges despite the myriad changes you put your body through every day.

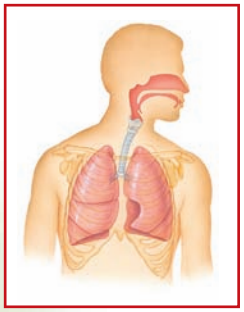
NATIONAL GEOGRAPHIC

Integumentary system
Main functions: provide protection, sense immediate environment, produce Vitamin D

Skeleto-muscular system
Main functions: provide movement, protection, mineral storage, heat production, and blood cell production

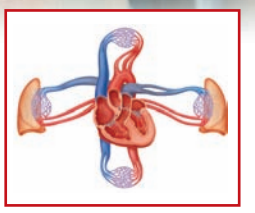


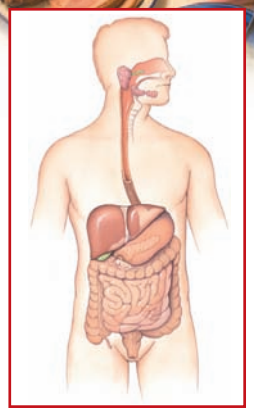
Nervous system
Main functions: receive and react to external and internal stimuli, integrate sensory information



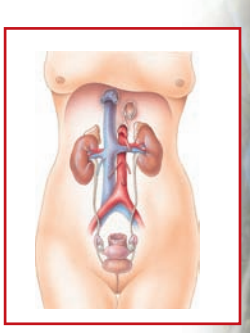
Respiratory system
Main functions: bring oxygen to the body and remove carbon dioxide, maintain blood pH

Cardiovascular system
Main functions: transport blood (nutrients, wastes, and dissolved gases) to and from tissues

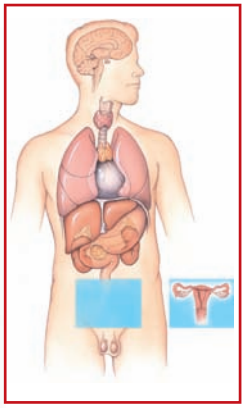




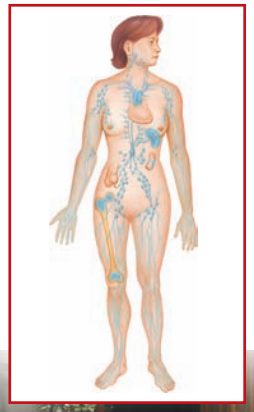
Digestive system
Main functions: absorb nutrients, vitamins, and minerals from ingested food



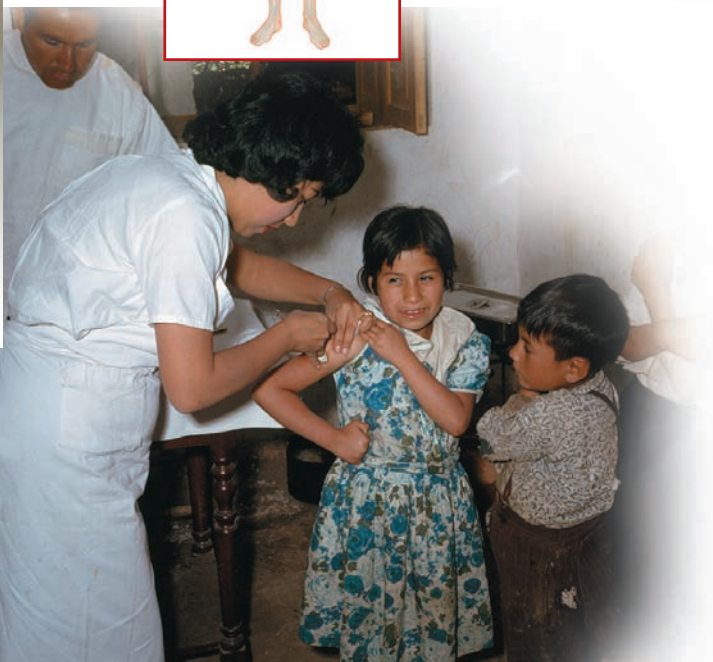
Urinary system
Main functions: maintain fluid balance and blood volume, composition, and pressure

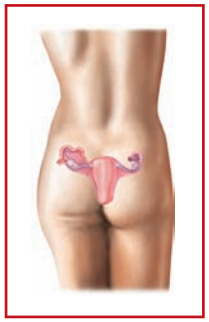


Endocrine system
Main functions: produce hormones to control events such as blood sugar levels, growth, and sexual maturity



Lymphatic system
Main functions: provide immunity, cleanse interstitial fluid





Reproductive system
Main functions: produce eggs and sperm, and secondary sexual characteristics, and provide for the embryonic development of offspring

WILEY PLUS Video

ETHICS AND ISSUES

Organ Transplants

There are essentially three ways to distribute any good or service for which there are more buyers than sellers:

- Price
- Utility
- Need

In a market economy, the law of supply and demand suggests that in such circumstances price rises to the point economists refer to as "equilibrium," where the number of sellers equals the number of buyers. This is what happens with houses, stocks, or commodities, such as oil and natural gas.

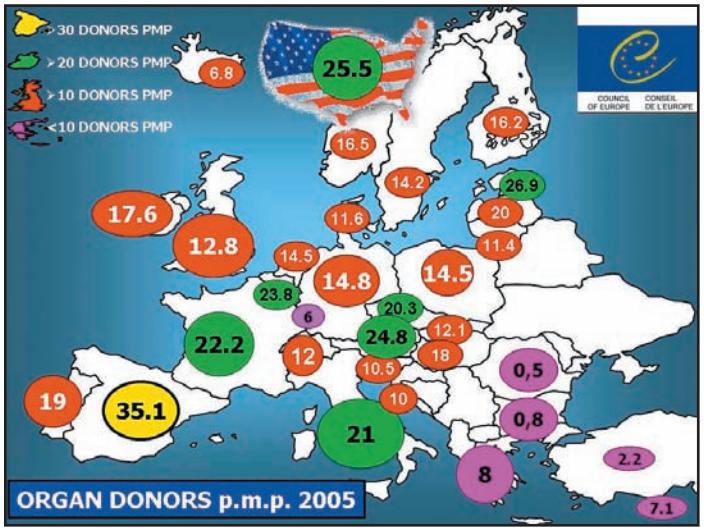
What happens when the "good" is a human organ? Ironically, in the most vibrant market economy on the Earth, Americans typically find something inherently wrong with the idea of selling a human organ.

Similarly, the philosophical concept of utility—"the greatest good for the greatest number"—seems inappropriate when the item at stake is something that is necessary to prolong life. Does the greatest good for the greatest number mean giving an organ to the person with the largest family? To the person whose work has a positive impact on the greatest number of lives? In a nation that cherishes individual liberty, human dignity, and justice, is the life of a prize-winning physicist truly worth more than the life of a bus driver?

In the United States, we base the distribution of organs for transplant on the third distribution system listed above: need. Organ banks around the country rank patients awaiting organs by the severity of their illness. As a person's condition deteriorates, he or she "moves up the list." Unfortunately, individuals also move up the list when someone higher on the list dies because no organ has become available.

Many doctors argue that those who are very ill are less likely to benefit from organ transplants than those who are less ill, and that young people can benefit more from an organ transplant than older people. They argue that "life years from transplant"—a candidate's estimated survival with and without a transplant—should be the key guideline.

The mismatch between available organs and the need for them is tremendous, as we see on the accompanying map, which shows the number of organ donors per million people (p.m.p) for some European countries and the United States. The gap is also growing daily. Each day, 12 Americans die waiting for a donor kidney. For hearts and lungs, which cannot be transplanted from living donors, the death toll among patients on the waiting list



is even worse. As a result, some Americans have taken to engaging in "medical tourism": traveling to less-developed countries to procure organs—mostly kidneys, of which each person has two—that are sold by the poor. Virtually every country has a black market for organs, as depicted in the movie *Dirty Pretty Things*.

The need-based distribution system is increasingly being bypassed in other ways as well. Especially for live-donor organs, media-savvy families take out advertisements and set up Web sites pleading the case of an individual in need. Especially when the person is a child, potential donors often appear in droves.

Critical Reasoning Issues It can be very difficult to look critically at basic and traditional assumptions—such as the norm that transplants go to the sickest patients. However, openness to new ideas is crucial to a full understanding of the issue.

Think Critically

1. Do you think taking out ads or setting up Web sites asking for donors is the same as "buying" an organ?
2. Should there be cutoff ages for receiving an organ? If so, what should they be? Would giving organs to younger or healthier patients be another form of utility-based reasoning?
3. A candidate for a liver transplant who was using medical marijuana was rejected by a transplant committee, which said the candidate might have an "addictive personality." Attack or defend the committee's decision.

CONCEPT CHECK STOP

1. **What** is the correct order of these terms—cell, molecule, organism, organelle, organ, tissue, organ system—from least complex to most?
2. **What** role do organ systems play in maintaining homeostasis?

5.3 Scientists Use a Road Map to the Human Body

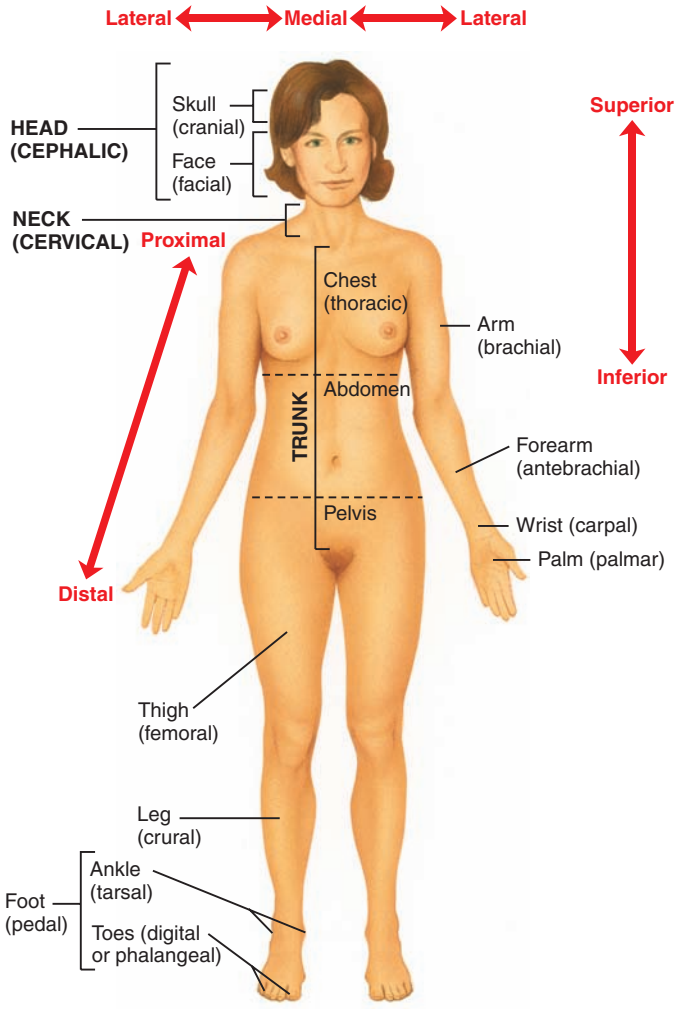
LEARNING OBJECTIVES

1. **Learn** to use anatomical directional terms.
2. **Identify** the body cavities and the organs that each contains.

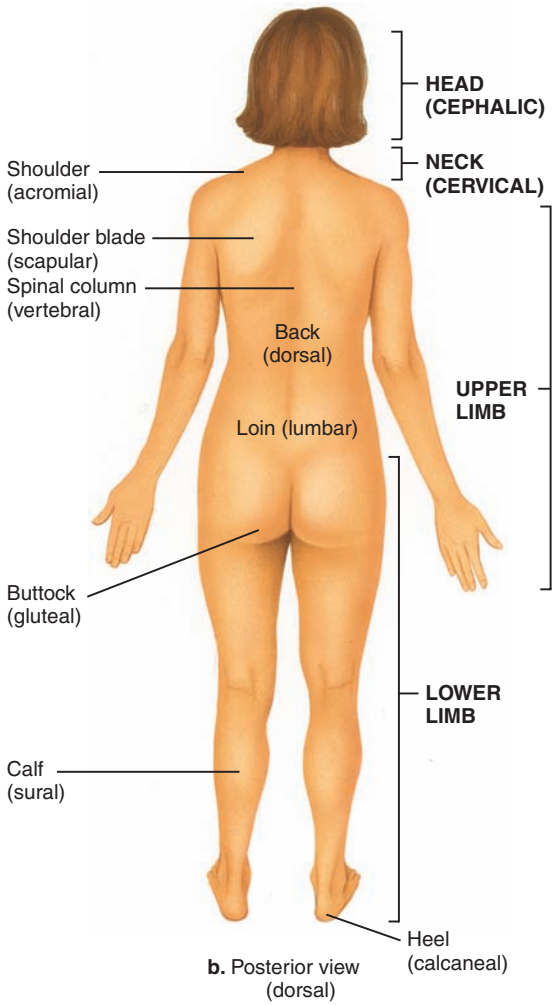
Studying human biology—human anatomy and physiology—is a daunting task because we are concerned not only with the location of organs and organ systems, but also their interconnection. To discuss these complicated matters clearly, we need a system to precisely name the structures of the body. Whenever we talk about an organ's placement, or the appearance of a portion of the body, we assume we have placed the body in the **anatomical position**, as shown in Figure 5.10. Using this position as a

Anatomical position with directional terms • Figure 5.10

In the "anatomical position," the bones of the forearm lie straight instead of crossing over one another as they do when our hands rest by our sides.



a. Anterior view (ventral)



b. Posterior view (dorsal)

standard allows us to make sense of directional terms, such as **proximal** and **distal**, **superior** and **inferior**, and **lateral** and **medial**.

The Body Has Two Large Cavities

We have a cavity that contains our brain and spinal cord, the dorsal cavity, and one that houses most of our internal organs, the ventral cavity. These cavities are shown in Figure 5.11. The body has natural boundaries that we exploit for describing position in human biology, including these two large cavities. The **ventral cavity** comprises the entire ventral (or belly) aspect of your torso. The ventral portion of the body contains distinct sections. The **thoracic cavity** includes the chest area and houses the heart, lungs, vessels, and lymphatic system of the **mediastinum**. The "guts" are found within the **abdominal cavity**, which is lined with **peritoneum**. The bladder and urethra of the urinary system and the reproductive system are located in the **pelvic cavity**.

proximal / distal Opposite terms meaning near the core of the body versus farther from the core.

superior / inferior Opposite terms meaning above and below.

lateral / medial Opposite terms meaning found near the side or found near the middle.

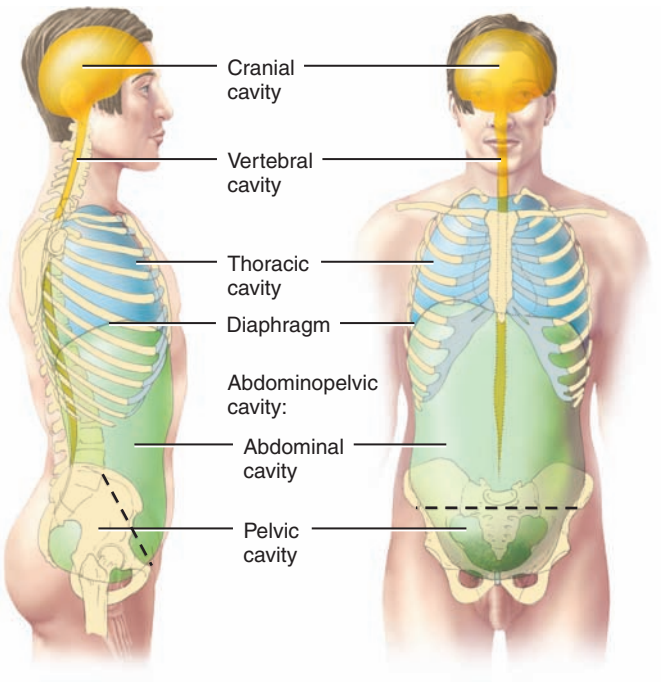
mediastinum The broad area between the lungs.

meninges Three protective membranes covering the brain and spinal cord.

The **dorsal body cavity** includes the **cranial** cavity housing the brain and the **vertebral** cavity containing the spinal cord. The **meninges** line these two continuous cavities.

Medical specialists often refer to the nine **abdominopelvic** regions of the body when diagnosing pain. Use of this terminology allows us to describe a particular area housing just a few abdominal organs, as shown in Figure 5.12.

Body cavities • Figure 5.11



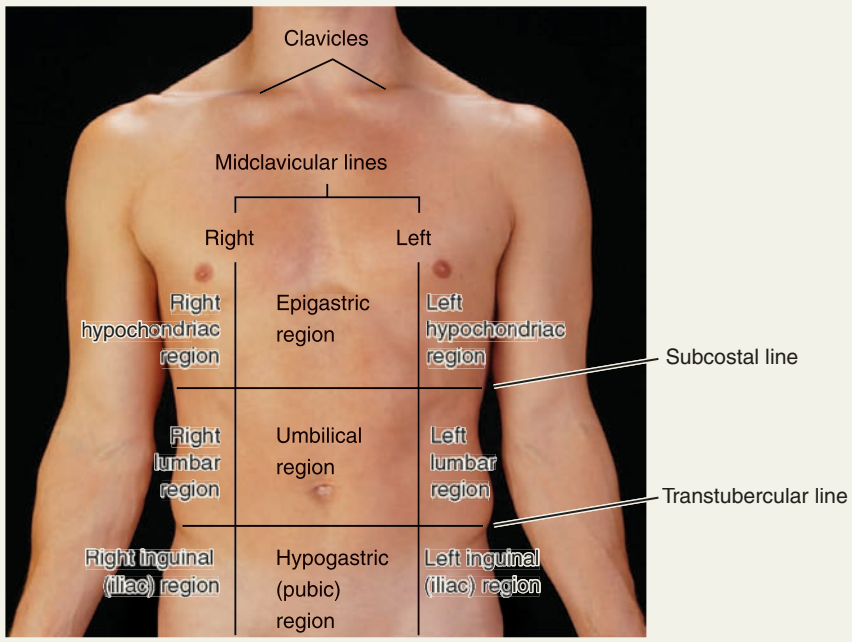
a. Right lateral view **b.** Anterior view

CAVITY	COMMENTS
Dorsal cavity	
Cranial cavity	Formed by cranial bones and contains brain.
Vertebral cavity	Formed by vertebral column and contains spinal cord and the beginnings of spinal nerves.
Ventral cavity (Thoracic and Abdominopelvic cavities)	
Thoracic cavity	Chest cavity; contains pleural and pericardial cavities and mediastinum.
Pleural cavity	Each surrounds a lung; the serous membrane of the pleural cavities is called the pleura.
Pericardial cavity	Surrounds the heart; the serous membrane of the pericardial cavity is called the pericardium.
Mediastinum	Central portion of thoracic cavity between the lungs; extends from sternum to vertebral column and from neck to diaphragm; contains heart, thymus, esophagus, trachea, and several large blood vessels.
Abdominopelvic cavity	Subdivided into abdominal and pelvic cavities.
Abdominal cavity	Contains stomach, spleen, liver, gallbladder, small intestine, and most of large intestine; the serous membrane of the abdominal cavity is called the peritoneum.
Pelvic cavity	Contains urinary bladder, portions of large intestine, and internal organs of reproduction.

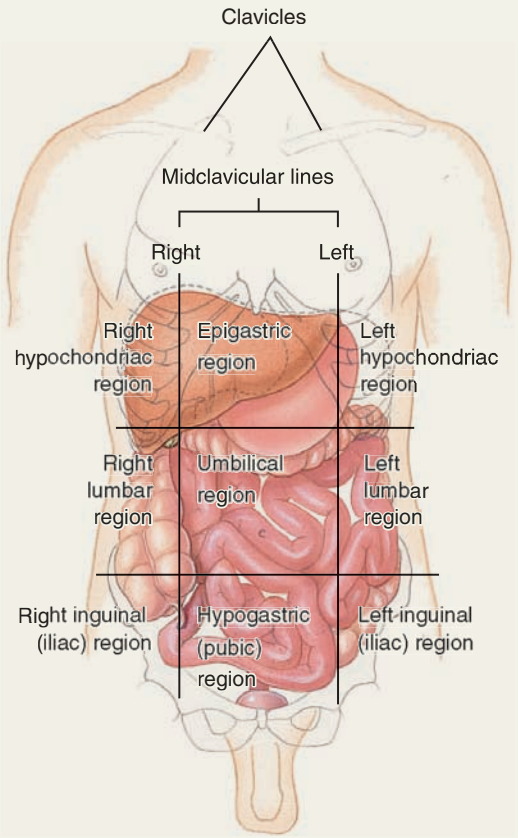
Biological InSight

The abdominopelvic regions • Figure 5.12

THE PLANNER



a. Anterior view showing abdominopelvic regions



b. Anterior view showing location of abdominopelvic regions

As we study human biology, we will refer to these regions and cavities as landmarks for identifying the position of organs and the relationships between them. This terminology also provides a common language to facilitate communication about location or organ function. In the coming age of computer-controlled surgery and online medical diagnoses, having a common language becomes even more important. Digital clinical assistance, or even distance education in this field, would be impossible without these conventions.

Knowing the organization of the chemicals, cells, and tissues that make up the human body is a prerequisite for understanding how humans function in the environment. Armed with this basic knowledge, an in-depth look at humans and their environment becomes much more interesting. Ultimately, the goal of this text is to explore the relationship between human physiology and the environment in which humans live.

CONCEPT CHECK

STOP

1. **What** does proximal / distal mean? Superior / inferior? Lateral / medial?
2. **What** are all the body cavities? The organs found within them?

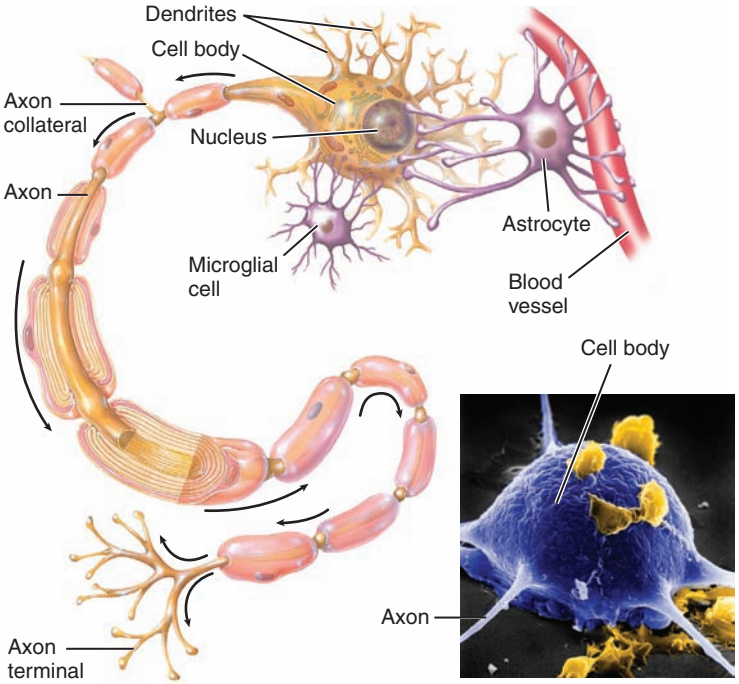
Summary

THE PLANNER

1 Cells Are the Building Blocks of Tissues 96

- The human body has four tissue types: epithelial, connective, nervous, and muscular.
- Epithelium covers and lines all body cavities and is classified based on cell shape (squamous, cuboidal, or columnar) and number of cell layers (simple or stratified).
- Connective tissue can be soft and loose or dense. Cartilage, bone, blood, and lymph are all examples of connective tissue.
- Muscular tissue can contract, and it comes in three varieties: smooth, skeletal, and cardiac muscle.
- Nervous tissue, as shown here, includes the impulse-carrying neurons and the neuroglia, which provide support for neurons.

Figure 5.8



2 Organization Increases with Organs, Organ Systems, and the Organism 107

- Tissues are grouped together in organs. Organs performing a similar function come together in organ systems. A group of organ systems comprises an organism.
- The 11 organ systems of the human are the skeletal (providing support and protection), muscular (aiding movement and heat generation), nervous (sensing and responding to the environment), integumentary (serving as a protective and sensitive layer), lymphatic (providing specific immunity), cardiovascular (transporting oxygen and nutrients to cells), respiratory (obtaining oxygen and removing carbon dioxide), digestive (obtaining nutrients), urinary (maintaining fluid balance), reproductive (producing new individuals), and endocrine (regulating sequential growth and development).

3 Scientists Use a Road Map to the Human Body 111

- When discussing the placement of human anatomical structures, we assume the body is in the anatomical position. This is a face-forward position, with the palms of the hands forward.
- The two main body cavities are the dorsal cavity and the ventral cavity. The dorsal cavity includes the cranial cavity, holding the brain, and the vertebral cavity, surrounding the spinal cord. The ventral cavity includes the thoracic cavity, the abdominal cavity, and the pelvic cavity. The ventral cavity can be subdivided into nine regions for specifically pinpointing the location of an organ, a structure, or a physiological event in the body.

Key Terms

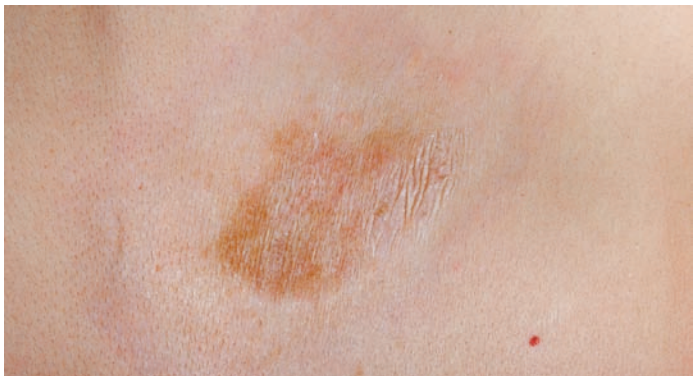
- avascular 99
- biceps brachii 103
- epiglottis 100
- interstitial fluid 101
- lateral/medial 112
- mediastinum 112
- meninges 112
- microvilli 96
- osteoid 101
- plasma 101
- proximal/distal 112
- rectus abdominus 103
- striations 103
- superior/inferior 112
- trachea 100

Critical and Creative Thinking Questions

1. **CLINICAL CLICK QUESTION**
   Although most of his teammates enjoyed the relief from muscle soreness that an icepack provided, Max hated to use ice on his athletic injuries. He found the experience painful, and his skin would go numb in a matter of minutes—a much faster and more severe response than his peers. As he became more aware of his skin, Max found patches of shiny, tight skin on his body. His physician suspected a disease of his connective tissues, causing loss of elasticity and narrowing of the blood vessels in his skin.

   What specific tissue type in Max's skin is experiencing problems?

   Further investigation indicated that Max's dermis had many more collagen fibers than expected. Review Section 5.1 to learn collagen's function in connective tissue. Explain why an overabundance of this protein will cause the skin to become tight, shiny, and less able to tolerate extreme cold. Visit http://www.mayoclinic.com/health/scleroderma/DS00362 to learn more about this disease that affects tissues.



2. The digestive tract has two surfaces: an inner surface that lines the gut and allows food to pass and an outer surface that separates the gut from the rest of the abdominal organs. What specific tissue would you expect to find on each of these surfaces? Would the inner surface have the same lining as the outer? Why or why not?
3. There are many types of connective tissue in the body, from adipose to bone to blood. What is it that makes these tissues different? More important, what are the unifying characteristics found in all connective tissues?
4. You are given the opportunity to create artificial skin in a laboratory to help burn patients. Remember that the skin must be protective, relatively watertight, and yet have some sensory function. What tissues will you need for this organ? Which type of epithelium will you use for the outer layer? What tissue will you need to house the blood vessels and the nerves? Will you need muscular tissue? Nervous tissue?
5. Physicians often use the regions of the body to diagnose pathologies. If a patient complained of stabbing pain in the abdominal cavity, which organs might be involved? Look at Figure 5.11 to help with your diagnosis. How would you describe the location of the urinary bladder using the nine abdominopelvic regions given in Figure 5.12?

What is happening in this picture?

"8.5; 7.0; 8.0" The average diving enthusiast sees a well-executed dive, with an almost flawless entry into the water. A scientist, however, notices the way the four tissues of the body communicate to perform exact, graceful, controlled motion.

NATIONAL GEOGRAPHIC

Think Critically

1. What two tissue types are responsible for the precise body positioning of this diver?
2. Are the other two tissue types involved in this activity at all? If so, how are they involved?
3. How does the structure of the epithelial tissue of the skin help maintain homeostasis as this diver enters the water?

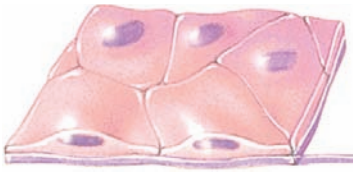
Self-Test

1. The four major tissue types that comprise the human body include all of the following EXCEPT _____.
   a. epithelial tissue
   b. muscular tissue
   c. areolar tissue
   d. nervous tissue
   e. connective tissue

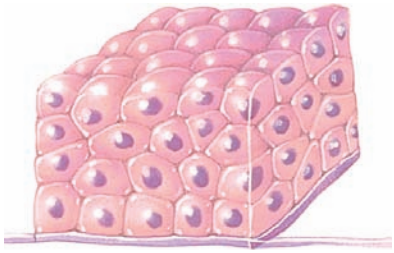
2. The tissue that can be found covering and lining openings in the body is _____.
   a. epithelial tissue
   b. muscular tissue
   c. areolar tissue
   d. nervous tissue
   e. connective tissue

3. The tissues that do not have a blood supply include _____.
   a. epithelial tissue only
   b. epithelial and connective tissue
   c. some types of connective tissue only
   d. epithelial and some types of connective tissue

4. The tissue type pictured is _____.
   a. stratified epithelium
   b. cuboidal epithelium
   c. simple epithelium
   d. columnar epithelium

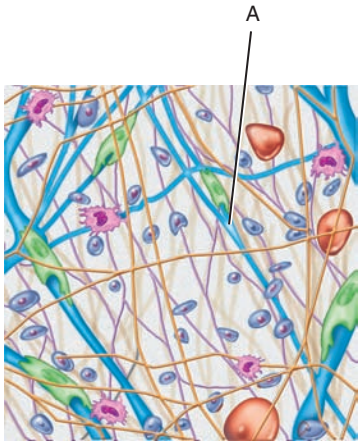


5. The function of the tissue pictured is most likely _____.
   a. a diffusion membrane
   b. a protective membrane
   c. a contractile organ
   d. a connective support

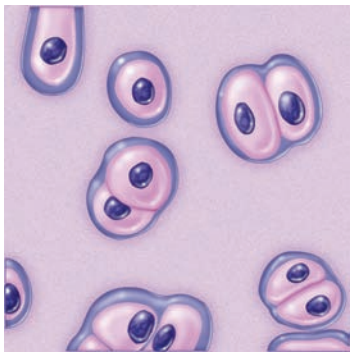


6. The specific type of cell that comprises most diffusion membranes is a _____.
   a. squamous epithelial cell
   b. cuboidal epithelial cell
   c. columnar epithelial cell
   d. exocrine cell

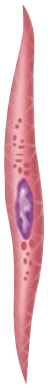
7. The structure labeled A in this diagram is _____.
   a. a fibroblast
   b. collagen fiber
   c. matrix
   d. a white blood cell



8. The type of connective tissue illustrated below is _____.
   a. bone
   b. hyaline cartilage
   c. elastic cartilage
   d. lymph
   e. fibrocartilage

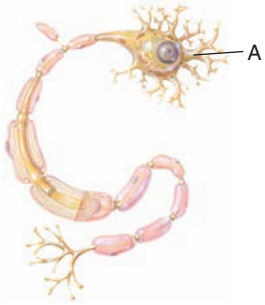


9. The tissue shown below is _____.
   a. hyaline cartilage
   b. skeletal muscle
   c. cardiac muscle
   d. smooth muscle



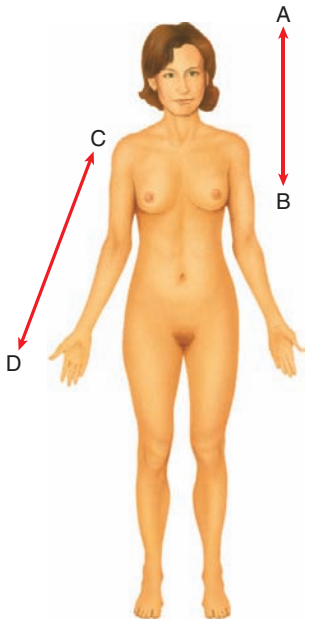
10. Which type of muscle tissue can be described as involuntary, striated, and connected via intercalated discs?
    a. skeletal muscle
    b. cardiac muscle
    c. smooth muscle
    d. Two of these have the listed characteristics.

11. Identify the structure labeled as A on this image.
    a. neuroglia
    b. dendrites
    c. axon
    d. neuron body



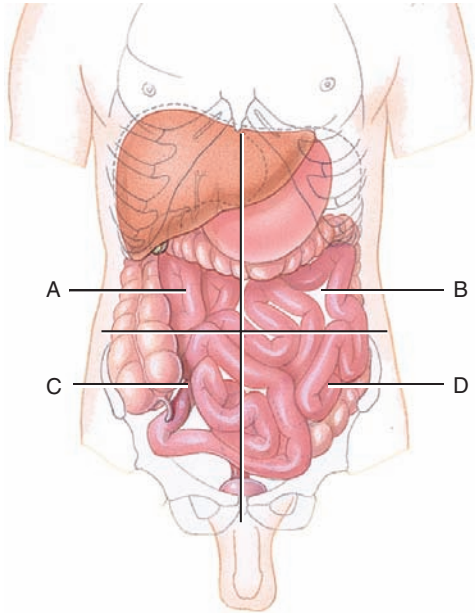
12. The correct order from least to most complex is _____.
    a. organ, organ system, organelle, organism
    b. cell, tissue, organism, organ system
    c. tissue, organ, organ system, organism
    d. cell, organelle, tissue, organ

13. Which term correctly describes the relationship indicated as A on this figure?
    a. superior
    b. inferior
    c. proximal
    d. distal



14. The _____ houses the heart, lungs, vessels, and lymphatics of the mediastinum.
    a. ventral cavity
    b. abdominal cavity
    c. cranial cavity
    d. thoracic cavity

15. Which label indicates the quadrant in which the majority of the liver lies?
    a. A
    b. B
    c. C
    d. D



THE PLANNER

Review your Chapter Planner on the chapter opener and check off your completed work.

WILEY PLUS Video

The Skeleto-Muscular System

Accuracy and speed are required to be a major league baseball pitcher. How fast can a baseball be accurately thrown? Nolan Ryan was the first baseball pitcher to be clocked throwing a baseball at speeds over 100 miles per hour. Is that as fast as is humanly possible, or can we expect faster pitches in the years to come? What did Nolan do differently that allowed him to achieve such incredible speeds? The answers to these questions lay in part with biomechanics, the field of science that studies biological motion through physics. Throwing an object requires the use of shoulder, back, chest, and arm muscles. These muscles apply force and torque (twist) to the bones of the chest, shoulder, and arm. Throwing a baseball with speed and accuracy also requires movement of the torso and legs, positioning of the head, and overall balance. In short, this one simple act requires the concerted effort of the entire body. Muscles must be trained to function immediately and at peak strength when triggered. They must also provide control and finesse by precisely pulling on the bones of the skeleton. The bones must, in turn, provide support for the muscles and leverage for the throwing motion. As muscles develop strength, the force they exert on the bones increases. The bones must respond by increasing in mass so as to relay that force rather than break under it. Human motion, both graceful and strong, is the result of smoothly functioning, integrated skeletal and muscular systems.

NATIONAL GEOGRAPHIC

CHAPTER OUTLINE

The Skeleto-Muscular System Is Multifunctional and Dynamic 120

- The Skeleto-Muscular System Is Vital to Survival
- The Skeleton Holds the Body Together While Muscles Provide Movement

Bone Is Strong and Light Tissue 122

- Bony Tissue Comes in Two Forms
- Bone Constantly Undergoes Remodeling and Repair

The Skeleton Holds It All Together 127

- The Axial Skeleton Is the Center of Things
- Vertebrae, Ribs, and Sternum Form the Balance of the Axial Skeleton
- Your Limbs Comprise Your Appendicular Skeleton
- Joints Link the Skeletal System Together

Skeletal Muscles Exercise Power 137

- Skeletal Muscle Is Built Like Telephone Cable
- Proteins Drive Muscles
- The Sarcomere Is Built for Contraction
- Contraction Starts with a Nerve Impulse
- The Contraction Cycle Continues as Filaments Slide Past One Another

Whole-Muscle Contractions Require Energy 144

- The Motor Unit Requires Multiple Stimuli
- Muscles Require Energy to Work Smoothly and Powerfully
- Muscle Twitches Can Be Fast, Intermediate, or Slow
- Toned Muscles Work Better, Look Better

CHAPTER PLANNER

- ❑ Study the picture and read the opening story.
- ❑ Scan the Learning Objectives in each section:
  p. 120 ❑ p. 122 ❑ p. 127 ❑ p. 137 ❑ p. 144 ❑
- ❑ Read the text and study all figures and visuals. Answer any questions.

Analyze key features

- ❑ Process Diagram, p. 122 ❑ p.142 ❑ p. 143 ❑
- ❑ Health, Wellness, and Disease, p. 126
- ❑ Ethics and Issues, p. 135
- ❑ Biological InSight, p. 138
- ❑ What a Scientist Sees, p. 146
- ❑ I Wonder..., p. 148
- ❑ Stop: Answer the Concept Checks before you go on:
  p. 121 ❑ p. 126 ❑ p. 136 ❑ p. 143 ❑ p. 148 ❑

End of chapter

- ❑ Review the Summary and Key Terms.
- ❑ Answer the Critical and Creative Thinking Questions.
- ❑ Answer What is happening in this picture?
- ❑ Answer the Self-Test Questions.

6.1 The Skeleto-Muscular System Is Multifunctional and Dynamic

LEARNING OBJECTIVES

1. **List** the functions of the skeleto-muscular system.
2. **Provide** examples of skeleto-muscular cooperation that promote survival in modern life.
3. **Describe** the interconnected structure of bone and muscle.
4. **Relate** movement to the structure of muscles.

Movement through the environment is a defining characteristic of animal life. Humans move by applying tension to the bones and joints of the skeletal system. This tension is applied by the muscular system, which is composed primarily of skeletal muscle tissue. When the brain asks muscles to contract, they pull on the bones, causing movement at the joints. Depending on the strength of those initial contractions, we perform many different types of movements. We use the skeleto-muscular system to propel us through our world in search of food, shelter, and clothing. Using the interplay between the bones and muscles of the face, we indicate whether we like or dislike a situation. We rely on strong muscles and bones to interact with the wealth of technological gadgets we use in daily life, from motorized vehicles to laptop computers and personal music devices.

By now it should be obvious that the skeletal system and the muscular system work as a unit to give us the ability to move and adapt to our environment. Specifically, the two systems work together to perform several key functions:

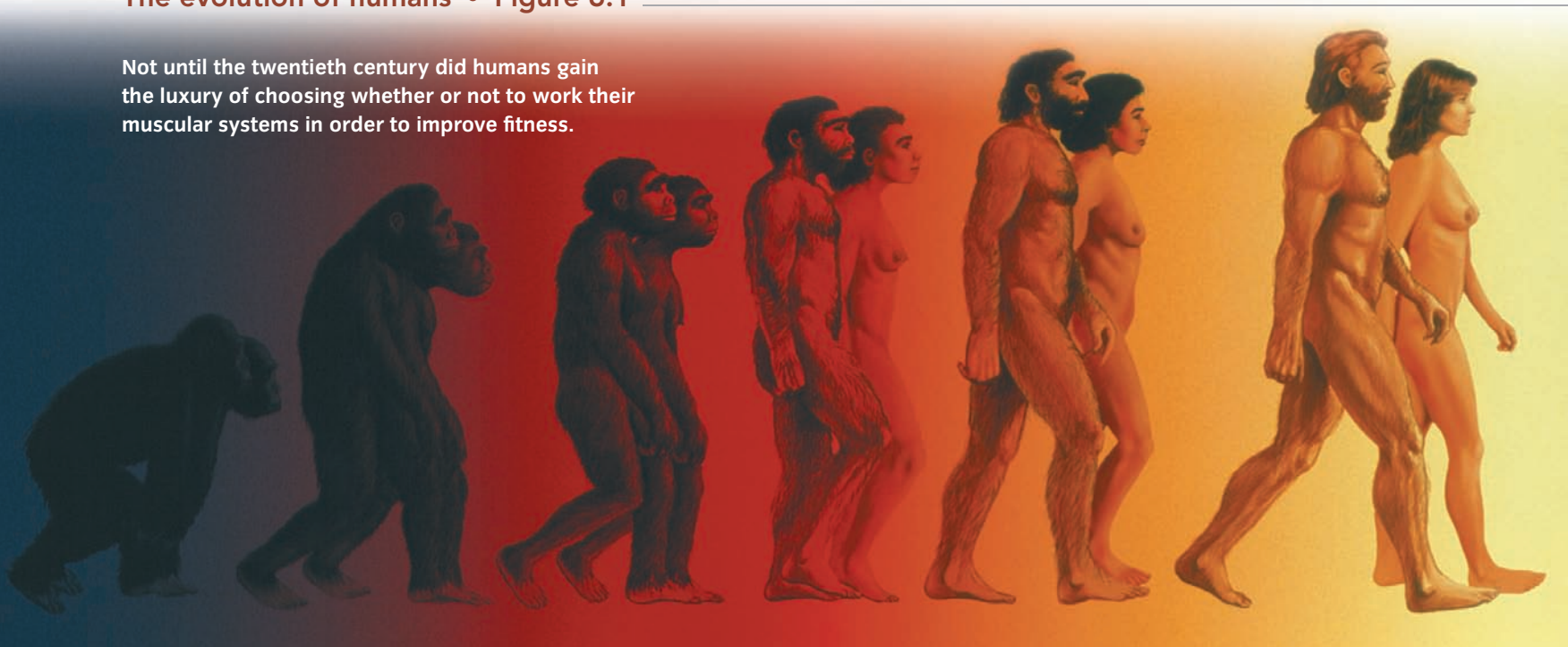
- Provide movement and locomotion
- Manipulate our environment
- Protect the organs in the thoracic and abdominopelvic cavities
- Help maintain homeostasis by generating internal heat
- Maintain our upright posture and bipedal way of life

In addition, the skeleton produces blood cells (a process called hematopoiesis) and stores and releases minerals, such as calcium and phosphorus, used in muscular contraction.

The Skeleto-Muscular System Is Vital to Survival

To see the skeleto-muscular system in the context of humans and their environments, consider how human life has changed in the past 20,000 years or so. See **Figure 6.1**. We

The evolution of humans • Figure 6.1



Not until the twentieth century did humans gain the luxury of choosing whether or not to work their muscular systems in order to improve fitness.

no longer live like other animals or even like our ancient ancestors, whose skeleto-muscular systems had to function at peak performance to provide nutrition and safety. Today technology helps us fulfill many of our needs and wants: We drive cars and ride bikes, use machines of all kinds, heat our homes, and wear protective clothing and athletic gear. Dependence on technology has the effect of lessening the demands on the skeleto-muscular system, but for the most part this does not substantially endanger our survival, at least in the short term.

However, our internal and external environments still make demands on us, and our bones and muscles must meet those demands by working together. Whether you are signing your name to a lease or pushing your disabled car off the road, you are using the combined forces of the skeletal system and the muscular system to create movement that increases your chances of survival. Society eases the demands placed on us by allowing us to survive through cooperative action; as a result, our individual movements require less force and more finesse.

Often, people become uncomfortable in a lifestyle that does not take full advantage of the combined strength of the skeleton and muscular systems, and they decide to begin an exercise program. When we begin a long-term exercise program, our bones and muscles respond in a way that improves our ability to perform exercise tomorrow. Should you begin a new exercise regime, you may be thinking about muscular or cardiovascular benefits, but athletic stress will also affect your bones. Extra support is added at locations where muscles exert a stronger pull, so skeletal strength matches muscular development.

The Skeleton Holds the Body Together While Muscles Provide Movement

How do the bones and muscles work together? Both bone and muscle are living tissue, but separately neither is able to produce movement. Muscular tissue **contracts**: It gets shorter. That is all it can do. When it contracts, it releases heat. Bone can be very dense or fairly light. It contains reserves of calcium and phosphate and can release them when needed. Bone can also protect soft tissues, forming a rigid case, but it cannot quickly alter the shape of that case. When the activities of these two tissues are combined, however, the result greatly exceeds their individual abilities.

Here are two simple examples of this interaction: The human body is able to dance in time to piano or guitar music, and it can delicately manipulate its fingers to play that music. See **Figure 6.2**. When a person is dancing, large muscles contract in specific patterns. These muscles are attached to specific bones of the skeletal system. When a muscle shortens, it pulls on the bone. Pulling on one bone causes movement at the accompanying joint. Other muscles are used to stabilize that movement and produce the grace and beauty of dance. Creating the music for that dance also requires the interaction of bones and muscles. When a person is playing the piano, the weight of the fingers is carefully and purposefully lifted and placed on specific keys, using specific muscles. These are smaller muscles, with less force but more precision. Additional force is added to this weight, again via muscles, to create melodic and pleasing sounds.

The dance of movement and support • Figure 6.2

Most people do not consider muscles to be organs, but they fit the definition: A muscle is composed of tissues that are combined to perform a specific job within the organism. All human skeletal muscles have a similar function and structure: They contract, or get shorter, to produce movement. Muscles can relax to their original ("resting") length or even elongate beyond that point. The covering on the muscle that defines it as a unique organ is continuous with the covering on the bone. When the muscle contracts, it must pull on the bone.

CONCEPT CHECK

STOP

1. **What** are the primary functions of the skeleto-muscular system?
2. **How** can you personally demonstrate the interaction between the skeleton and the muscles?
3. **How** are bone and muscle anatomically interconnected?
4. **What** arrangement of muscle and bone allows for efficient movement?

6.2 Bone Is Strong and Light Tissue

LEARNING OBJECTIVES

1. **Differentiate** compact from spongy bone tissue.
2. **Identify** the parts of a typical long bone.
3. **Describe** the formation of a typical long bone.
4. **Explain** the steps in bone remodeling and repair.

Bones are a form of connective tissue produced by immature bone cells called **osteoblasts**. Ossification—bone formation—can be **endochondral** or **intramembranous**. Most of your bones are endochondral, meaning that they were formed within cartilage. This process is outlined in Figure 6.3.

osteoblasts Immature bone cells not yet surrounded by bony matrix.

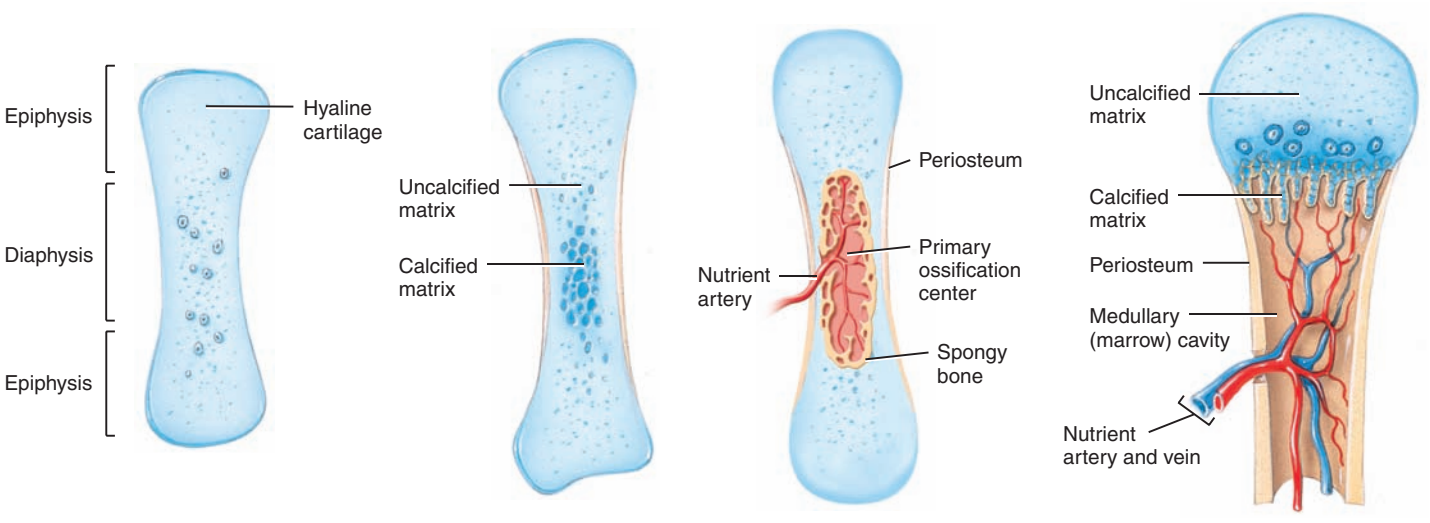
osteocytes Mature bone cells surrounded by bony matrix.

Not only do long bones grow longer, they also grow thicker. This growth occurs at the outer surface of the bone. Cells within the membrane that covers the bone, the **periosteum**, differentiate into osteoblasts and begin to add matrix to the exterior. Accumulating matrix entraps these osteoblasts, which mature into **osteocytes**, creating new bone tissue around the exterior of the bone.

PROCESS DIAGRAM

THE PLANNER

Endochondral ossification • Figure 6.3



1 Development of cartilage model

2 Growth of cartilage model

3 Development of primary ossification center

4 Development of the medullary (marrow) cavity

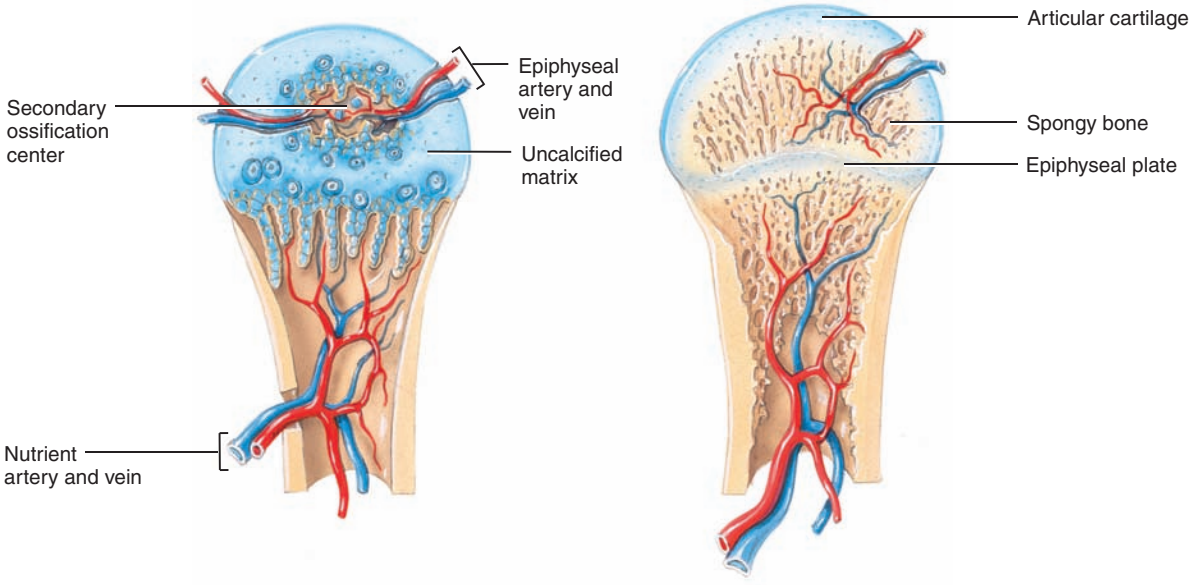
1. In endochondral ossification, a hyaline cartilage model of each bone forms in the embryo.
2. The hyaline cartilage model expands into the space the final bone will occupy.
3. A blood vessel invades the central portion of the model, stimulating osteoblasts to begin producing bone.
4. The marrow cavity forms.

Intramembranous ossification forms the flat bones of the skull, clavicle, and mandible. Again, the name suggests how the process occurs. Bone is laid down within embryonic connective tissue. These bones form deep in the dermis of the skin and thus are often called dermal bones. Dermal bones may also form in the connective tissues of joints, in the kidneys, or in skeletal muscles when subjected to excessive stress.

Bony Tissue Comes in Two Forms

Bone structure may be compact (dense) or spongy. Compact bone material usually occurs at the edges of the bone and is composed of many individual **osteons**. These are concentric rings of matrix laid by osteocytes and formed surrounding a central canal. Despite its strength and inflexible structure, bone is living tissue, and as such the cells within the bone must receive a constant nutrient supply and be able to dispose of wastes. They require a blood supply just like all other living cells. The central canal of the osteon houses the blood and nerve supply for the bone tissue. Individual cells lie within small holes in the matrix. Because tissue cells must contact one another, bone cells communicate via small canals cut into the matrix. These canals allow fluid carrying vital nutrients and signaling chemicals to pass between cells. Osteons communicate via larger perforating canals that run perpendicular to the long axis of the osteons and connect one central canal with the next.

In a typical bone, dense bone surrounds the organ, and spongy bone comprises the inner support. Spongy bone is less organized than compact bone and lacks osteons.



5 Development of secondary ossification center

6 Formation of articular cartilage and epiphyseal plate

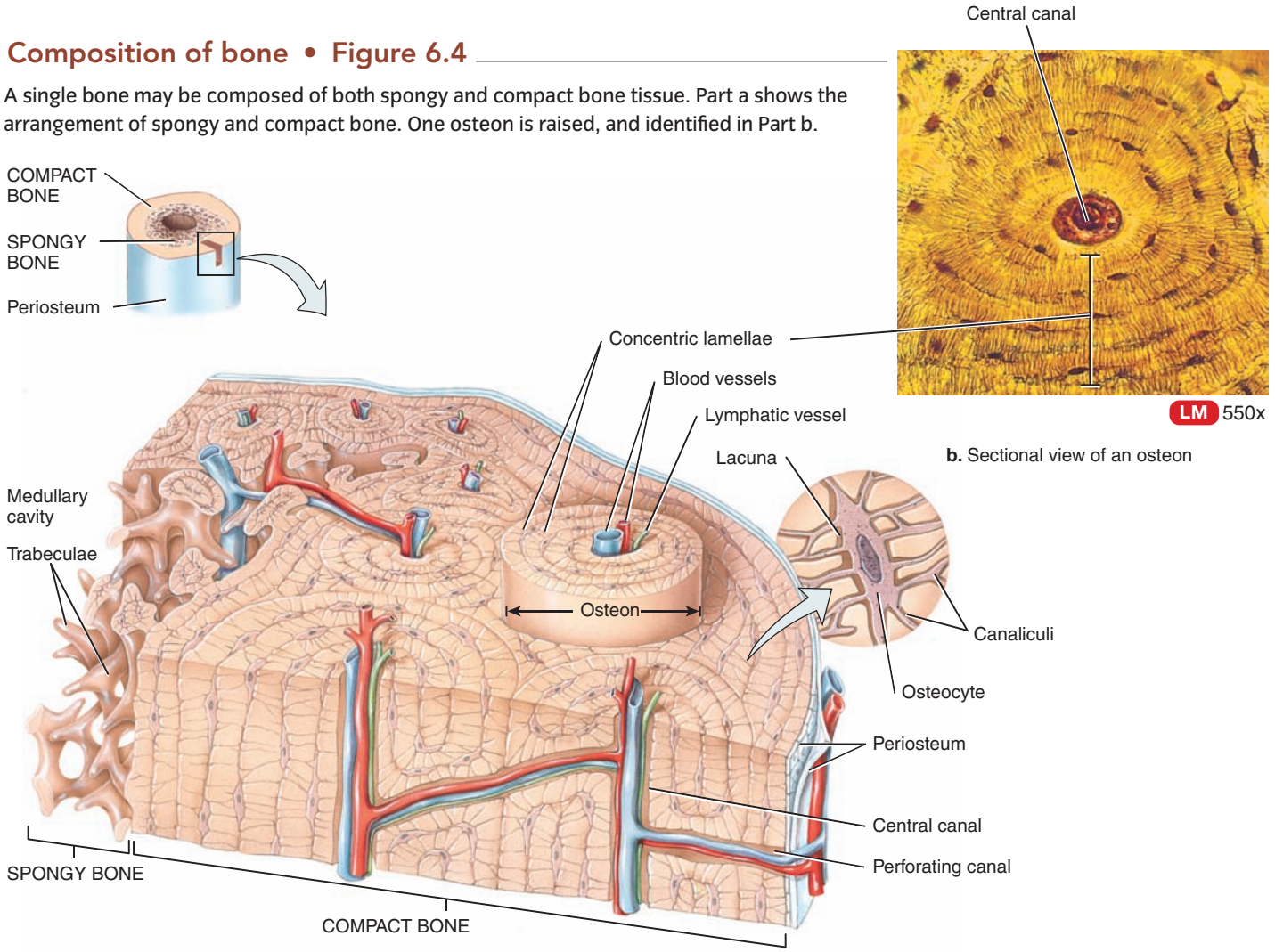
5 After birth, a second blood vessel invades each end of the developing bone, again stimulating osteoblast activity.

6 The epiphyses (long bone ends) are ossified, leaving a central area of cartilage called the epiphyseal plate, which continues growing through adolescence. Cartilage on the surface of the epiphyses also remains, forming articular cartilage.

At maturity, the epiphyseal plate closes and the bone's length is essentially static.

Composition of bone • Figure 6.4

A single bone may be composed of both spongy and compact bone tissue. Part a shows the arrangement of spongy and compact bone. One osteon is raised, and identified in Part b.



a. Osteons in compact bone and trabeculae in spongy bone

b. Sectional view of an osteon

Instead, spongy bone has **trabeculae**, or struts, that form in response to stress. These struts are composed of osteocytes surrounded by matrix similar to the osteon of compact bone. Instead of being laid in concentric rings, the matrix looks like short, interconnecting support rods. Figure 6.4 illustrates the structure of both spongy and compact bone.

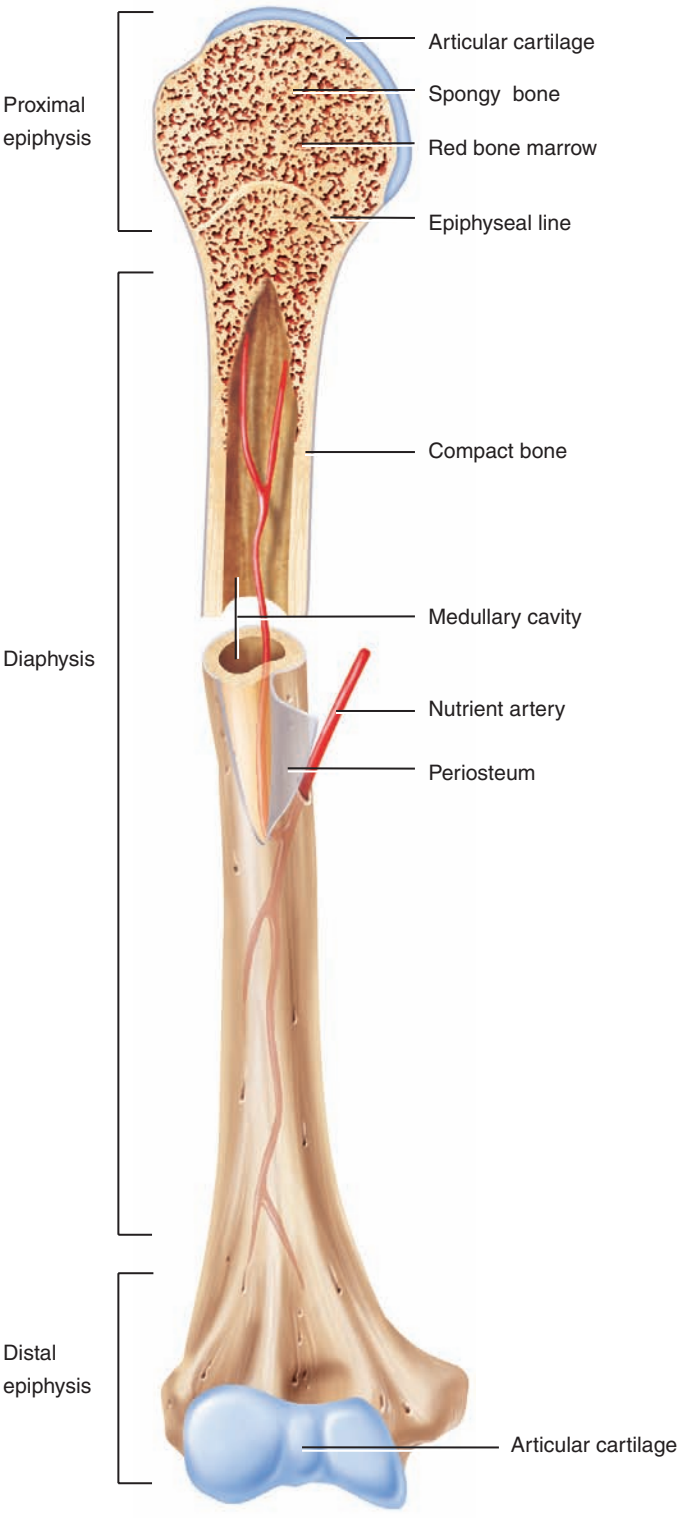
The shaft of a long bone is composed of dense bone surrounding a central canal, the medullary canal. In mature bones, the medullary canal of the long bone houses yellow marrow; blood cells form at the **epiphyses** in red marrow, and energy is stored in yellow marrow. The ends of the bones, or epiphyses, include the **epiphyseal plate**, an area of cartilage where long bones continue to grow during childhood and adolescence. When bones cease growing, this cartilage is replaced by bone, leaving the **epiphyseal line**. Wherever two bones meet, you will find a layer of hyaline cartilage. This **articulating cartilage** prevents bone from grinding against bone at a joint. Figure 6.5 identifies these structures.

Bone Constantly Undergoes Remodeling and Repair

Bones are dynamic structures, constantly being remodeled and perfected to suit the needs of the body, and continuously making subtle changes in shape and density to accommodate your lifestyle. Although long bones cease growing in length at maturity, they do change shape throughout life. The calcium within each bone is removed and new calcium is added in response to blood calcium levels and the amount of stress placed on the bones.

Long bone • Figure 6.5

All long bones have a similar structure, as shown here.



Partially sectioned humerus (arm bone)

Remodeling of existing bone is different from original ossification. Remodeling takes advantage of the interplay between **osteoclasts** and osteoblasts. Osteoclasts are large cells that adhere to the surface of bony tissue and release acids and enzymes. The end result of the activity of these cells is the breakdown of the bony matrix and the addition of calcium and other minerals to the bloodstream. Osteoblasts build the mineral structure back up, pulling calcium and minerals from the bloodstream. The osteoblasts first secrete an organic matrix called osteoid. They then cause an increase in local calcium concentration around the osteoid, converting the osteoid to bone. This process takes up to three months to complete. As usual, rebuilding takes much longer than destruction, but the overall outcome of osteoclast and osteoblast activity is a cyclic process that tears down and rebuilds the bony matrix.

The bones are a storehouse for calcium needed in physiological processes, such as nerve impulse transmission and muscle contraction. When the blood calcium level drops, osteoclasts go to work to release stored calcium to the blood. Conversely, when the blood calcium level rises, the osteoblasts create new matrix, removing excess calcium from the blood.

The repair process is a drastic version of the remodeling process. For bone to heal, the ends of the fracture must be aligned and immobilized. When alignment is possible without disturbing the skin, the process is called "closed reduction." In "open reduction," the skin must be cut, and often metal screws, plates, or pins are used to fix the bones in place. Open reduction is more likely to be needed in "compound fractures," which have more than one break and often include a tear or opening in the skin with the original injury. After either type of reduction, a cast, splint, or other external paraphernalia is generally needed to immobilize the fracture.

Still, complete immobilization may not be ideal for healing bone. Limited movement, stress, or partial weight-bearing activities can actually help the bones grow, because those stresses on the bone matrix stimulate bone deposition. See *Health, Wellness, and Disease: How Does a Broken Bone Heal?* on the next page.

HEALTH, WELLNESS, AND DISEASE

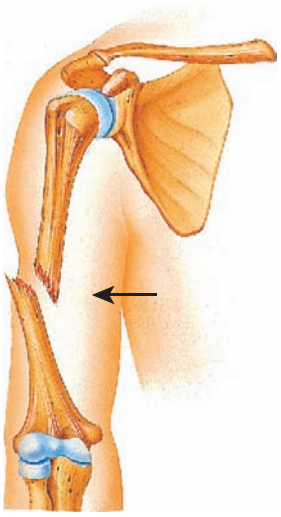
WILEY PLUS Video

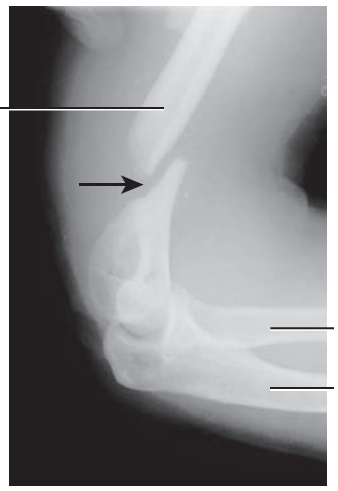
How Does a Broken Bone Heal?

Broken bones are pretty common, especially among the elderly and active children and young adults. The most common types of broken bones are *closed fractures* in which the bone does not break the skin, *open fractures* where the bone extends from the skin (Figure a), and *comminuted* fractures in which the bone remains within the skin but is crushed (Figure b). In each case, the break must heal before the bone is able to function.

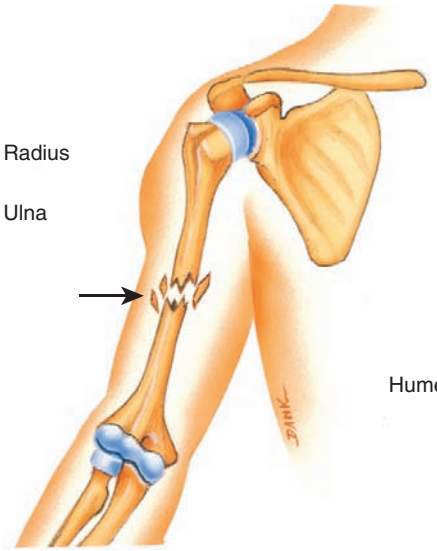
How does a broken bone heal? Bone repair occurs in four stages:

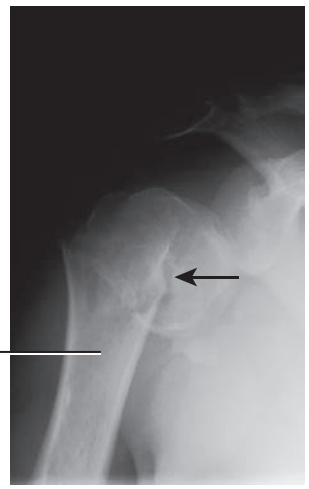
1. **Fracture hematoma forms.** Blood leaks from broken vessels near the fracture, and a clot forms within a few hours of the break. Dead blood cells accumulate, and other blood cells start to remove them.
2. **Fibrocartilaginous callus forms.** Actual repair begins as fibroblasts are produced by the periosteum and start making collagen fibers. Immature cartilage cells, also derived from the periosteum, start to make new cartilage. Within about three weeks of the injury, a fibrocartilaginous callus forms from these two types of connective tissue.
3. **Bony callus forms.** Osteoblasts start to produce spongy bone tissue at the ends of the broken bone, beginning in areas with healthy bone and good vascularization. Fibrocartilage also converts into spongy bone tissue.
4. **Bone remodels.** Osteoclasts gradually resorb dead bone tissue from the damage site. Spongy bone is converted into compact bone. The healed bone is often thicker and stronger than the original bone. The callus remains as a visible thickened bump on the bone for many years after the break is healed.





a. Open fracture





b. Comminuted fracture

CONCEPT CHECK

STOP

1. **What** is the difference between spongy and compact bone?
2. **Which** part of a typical long bone includes the red marrow? **Where** is the articular cartilage found?
3. **How** is a typical long bone formed?
4. **How** are bone remodeling and bone repair related?

6.3 The Skeleton Holds It All Together

LEARNING OBJECTIVES

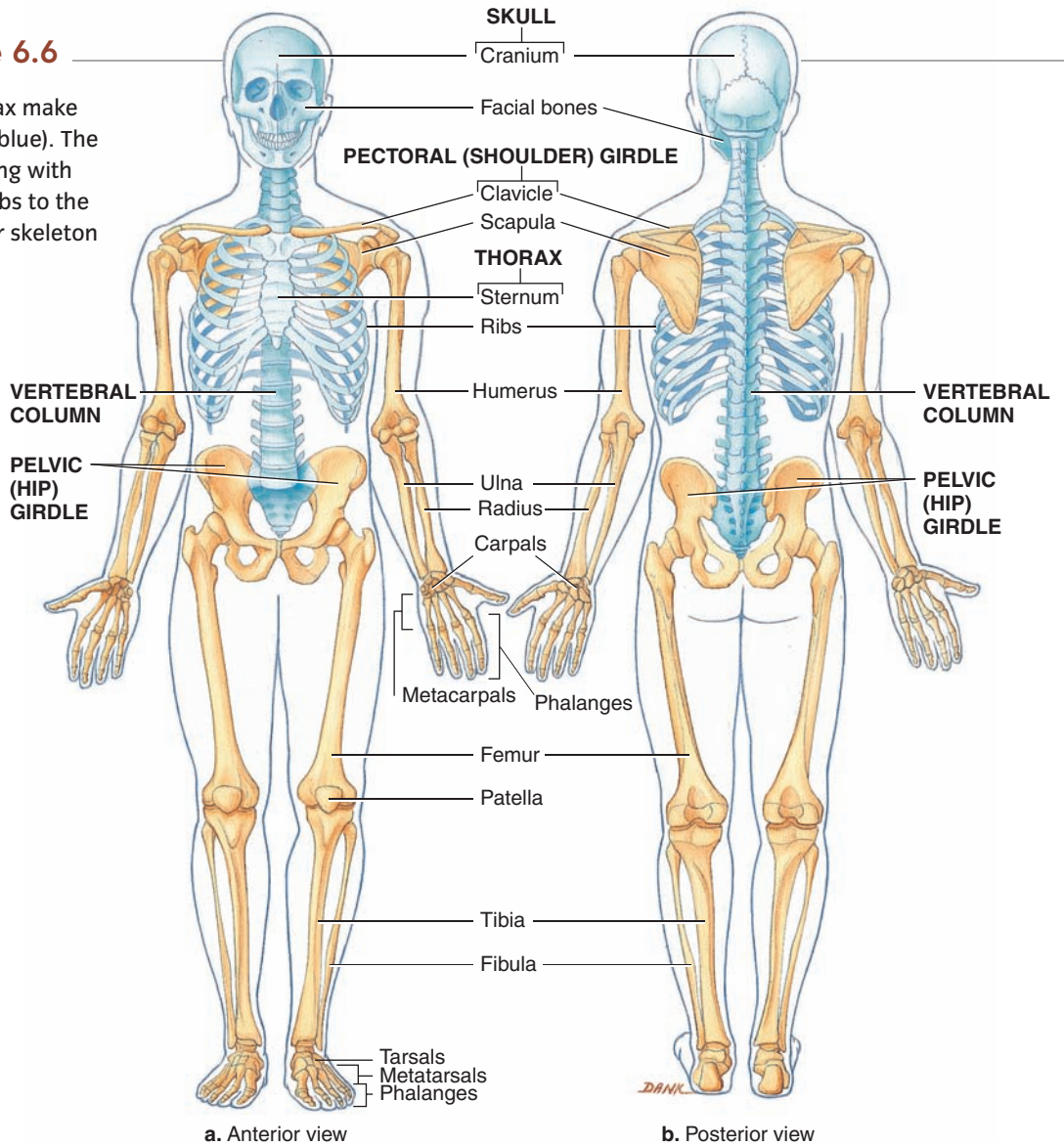
1. **Define** the divisions of the skeletal system.
2. **Identify** the major bones of the body.
3. **Compare** the characteristics of the pelvic and pectoral girdles.
4. **Discuss** the different types of joint and the movement provided by each.

Two hundred and six named bones comprise the skeleton that underlies the adult human form. This number varies a bit from person to person because small bones can exist within some tendons. The skeleton is divided into the **axial** skeleton (the central axis of the body) and the **appendicular** skeleton (the appendages—arms, legs, hands, and feet—and girdles holding them to the central axis). These two divisions are shown in **Figure 6.6**.

In the body, "form follows function," and this is nowhere more true than in the skeletal system. Every bone in your body is designed to perform a specific task. For

The skeleton • Figure 6.6

The bones of the skull and thorax make up the axial skeleton (shown in blue). The arms, hands, legs, and feet, along with the bones that secure these limbs to the body, make up the appendicular skeleton (shown in beige).



a. Anterior view **b.** Posterior view

example, the long bone known as the femur must be strong and have a slight anterior curve to bear the weight of the upper torso. The bones of the skull must curve into a "bowl" that houses and protects the brain. We classify the bones according to shape:

1. Long bones are longer than they are wide.
2. Short bones like those of the wrist are akin to small cubes.
3. Flat bones are very thin in one dimension.
4. Irregular bones have odd shapes.
5. Sesamoid bones form inside tendons.
6. Wormian bones are embedded in the sutures between the main skull bones.

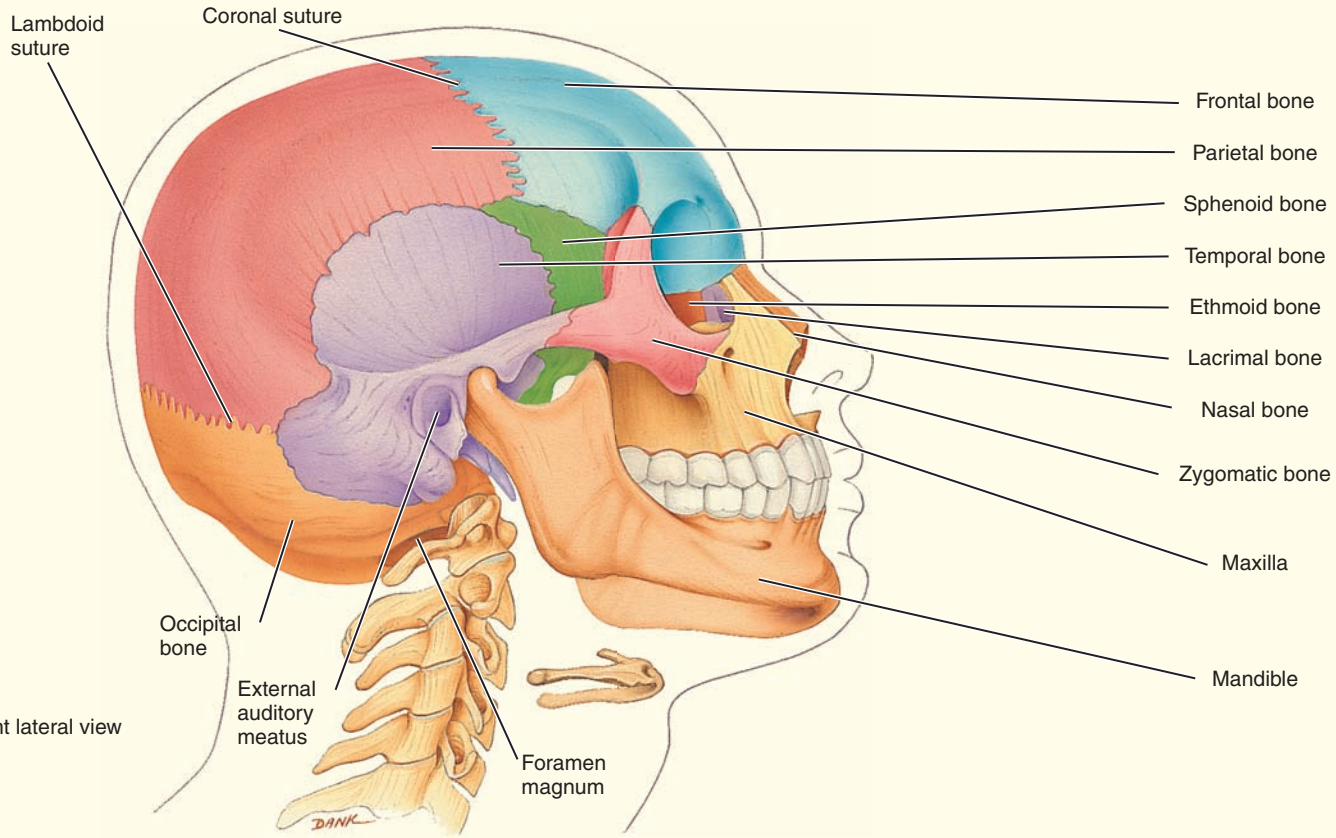
Sesamoid bones are yet another example of the strong interplay between bones and muscles. When muscles and their attaching tendons rub against underlying bone, the tendon can be damaged. To protect the tendon and prevent further damage, often a new bone is formed. Your kneecap is just such a bone, formed to protect your quadriceps tendon from the rough ends of the femur and tibia as you began to move your leg. Women who wear high heels often will develop small sesamoid bones at the underside of their great toe, again to protect the tendon that passes there and flexes the toe.

The Axial Skeleton Is the Center of Things

The axial skeleton includes the 8 cranial and 14 facial bones as well as the hyoid bone, ribs, and vertebrae. The cranial bones protect our brain, and the facial bones help give us identity. The hyoid is the only bone in the skeleton not attached to any other bone, while the ribs and vertebrae give us our upright posture and protect the organs in our thoracic cavity.

Cranial bones, collectively known as the skull, surround and protect the brain. Of these cranial bones, the parietal and temporal bones are paired, whereas the frontal bone, occipital bone, ethmoid, and sphenoid are single bones. All eight cranial bones are held together by fixed joints called **sutures**. Refer to Figure 6.7 as you read about the anatomy of the skull.

The cranial and facial bones • Figure 6.7



The **frontal** bone at the forehead protects the frontal lobe of the brain. The frontal bone originates as two frontal bones that start fusing in early development. This fusion continues so that by age eight or so, the suture is difficult to locate. The frontal bone can be the source of misery—when the lining of the large sinuses in the frontal bone becomes inflamed, you get a sinus headache.

The **parietal** bones protect the upper sides of the head, whereas the temporal bones protect the middle sides of the head and support the ears. These bones underlie the areas commonly referred to as the temples. The lower jaw (mandible) **articulates** with the temporal bones. The mandible is the only bone of the skull that is not fused to the rest.

parietal Of or relating to walls of a cavity, as in the walls of the cranial cavity; also, a parietal part.

articulates Joins; an articulation is a joint holding two bones together.

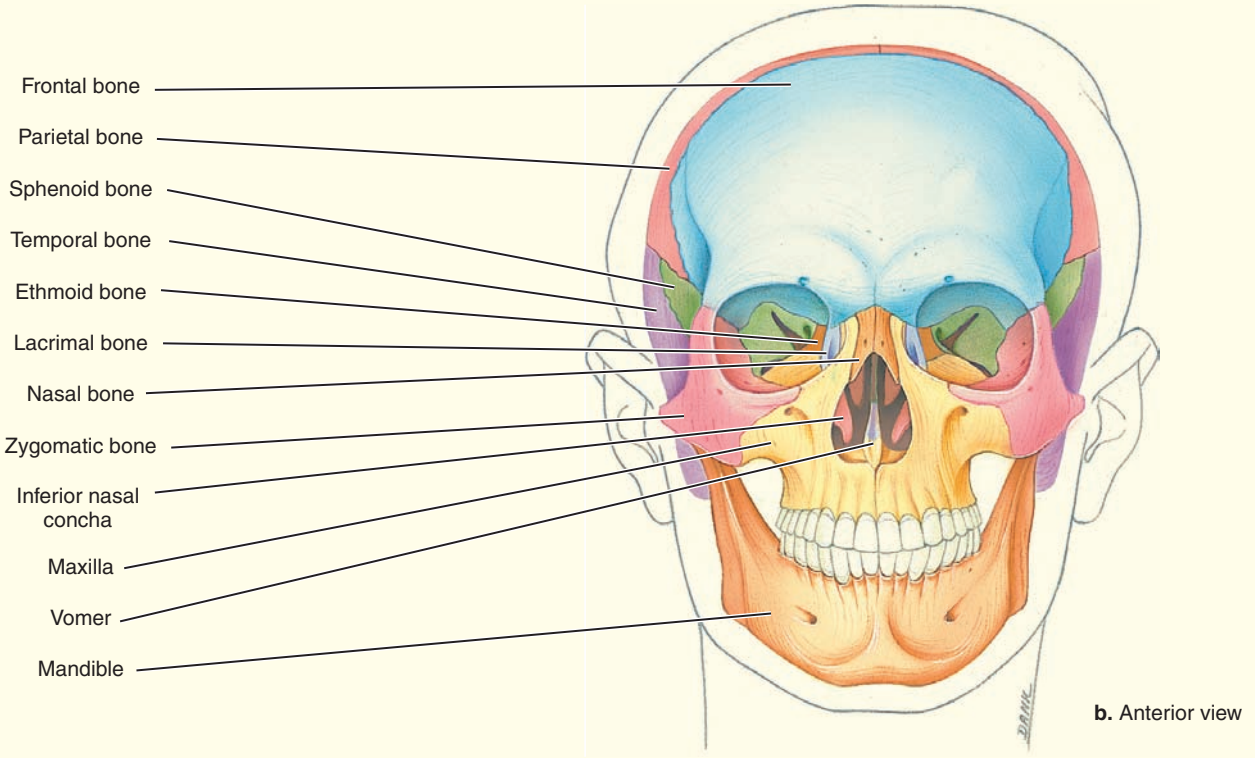
The entire back of the skull is a single bone, called the **occipital** bone. An opening in this bone, called the **foramen magnum** (big hole), allows the spinal cord to extend from its protective cranium into the vertebral foramen.

Two cranial bones comprise the floor of the brain bucket, or cranial cavity. The **ethmoid** forms the floor of the front portion of the cranial cavity. It articulates with the frontal bone and a few bones of the face. The **cribriform plate** lies within the ethmoid. This unique sieve-like structure allows olfactory nerves to extend from the olfactory bulb of the brain into the mucous membrane of the nasal passageway.

cribriform plate A fragile, porous area of the ethmoid bone at the superior portion of the nasal cavity.

The final bone of the cranium, the **sphenoid**, articulates with all other cranial bones. The sphenoid provides the base for the cranium, supporting the brain. It is shaped somewhat like a bat.

The 14 facial bones support the distinctive features we so closely associate with our own identity. Anatomically, the facial bones protect the entrances to the respiratory and digestive systems, and the sensory organs. Two facial bones are single, and 12 occur in pairs. The paired **maxillae** and **palatine** bones make up the front (maxillae) and roof of the mouth (the palatine bones).



b. Anterior view

The small, thin, paired **nasal** bones form the bridge of the nose. Because of their thin shape, if these bones are struck hard enough, they can penetrate the skull through the cribriform plate immediately superior to them.

On either side of the nose are the small, paired **lacrimal** bones. The root of this word, *lacrima*, means tears. A small passage in these bones allows the tears to collect and pass through the skull into the nasal cavity.

Your cheekbones are among the most memorable facial features, since they create the relief and depth of your face. These bones, the paired **zygomatic** bones, bulge outward and help protect the eyes. A blow to one of these bones can cause a black eye.

Within the nasal cavity lies the final pair of facial bones, the **inferior nasal conchae** (a conch is a snail with a helical shell). These bones form the swirling surface of the nasal cavity, helping to warm and moisten the air we inhale. The **vomer** is the bony separation between nasal passages. A deviated septum, or broken nose, occurs when the cartilage that this bone supports shifts from its central location to block one passageway.

The **mandible**, the only bone of the skull attached by a movable joint, articulates with the mandibular **fossae** (singular: *fossa*) of the temporal bone at the temporomandibular joint (TMJ). The mandible has small holes that allow our lower teeth to be supplied with nerves and blood.

fossa A pit, groove, or depression.

The single **hyoid** bone, which lies below the tongue, is the only bone of the skeleton that is not directly attached to any other bony structure. The hyoid bone is instead suspended by the throat muscles. This bone is of forensic interest because it can reveal death by strangulation; it is crushed only by pressure applied to the throat.

Vertebrae, Ribs, and Sternum Form the Balance of the Axial Skeleton

The remainder of the axial skeleton is composed of the **vertebrae**, **ribs**, and **sternum**. These bones allow upright posture and protect vital organs of the thoracic cavity.

There are 24 vertebrae, one sacrum, and three to five coccyx bones in the adult vertebral column.

A typical vertebra is composed of three parts: the **vertebral body**, the **vertebral arch**, and the **vertebral articular processes**. The articular processes serve as points of attachment between adjacent vertebrae and sites for muscle attachment. The column is divided into the cervical region (vertebrae C1–C7), the thoracic region (T1–T12), and the lumbar region (L1–L5). Moving down the column, the bodies of the vertebrae grow larger, because they must support more weight. Between each vertebra is a pad of fibrocartilage called the intervertebral disc. The disc serves as a shock absorber, preventing vertebrae from rubbing against one another and crushing under the body's weight. These discs also allow limited motion between vertebrae.

The sacrum is actually five fused vertebrae that form a solid base for the **pelvic girdle**, with openings along their length for the exit of sacral nerves. The tailbone, or coccyx, is our post-anal tail. (As mammals, we must have a tail, although it is hardly obvious!) Our tail is made of three to five small bones that extend off the sacrum, completing the inner curve of the pelvis. In females, these bones are tilted further outward than in males, so they do not interfere during childbirth. Even so, some infants break their mother's coccyx during childbirth.

pelvic girdle The bones that connect the leg to the axial skeleton; the hip bones.

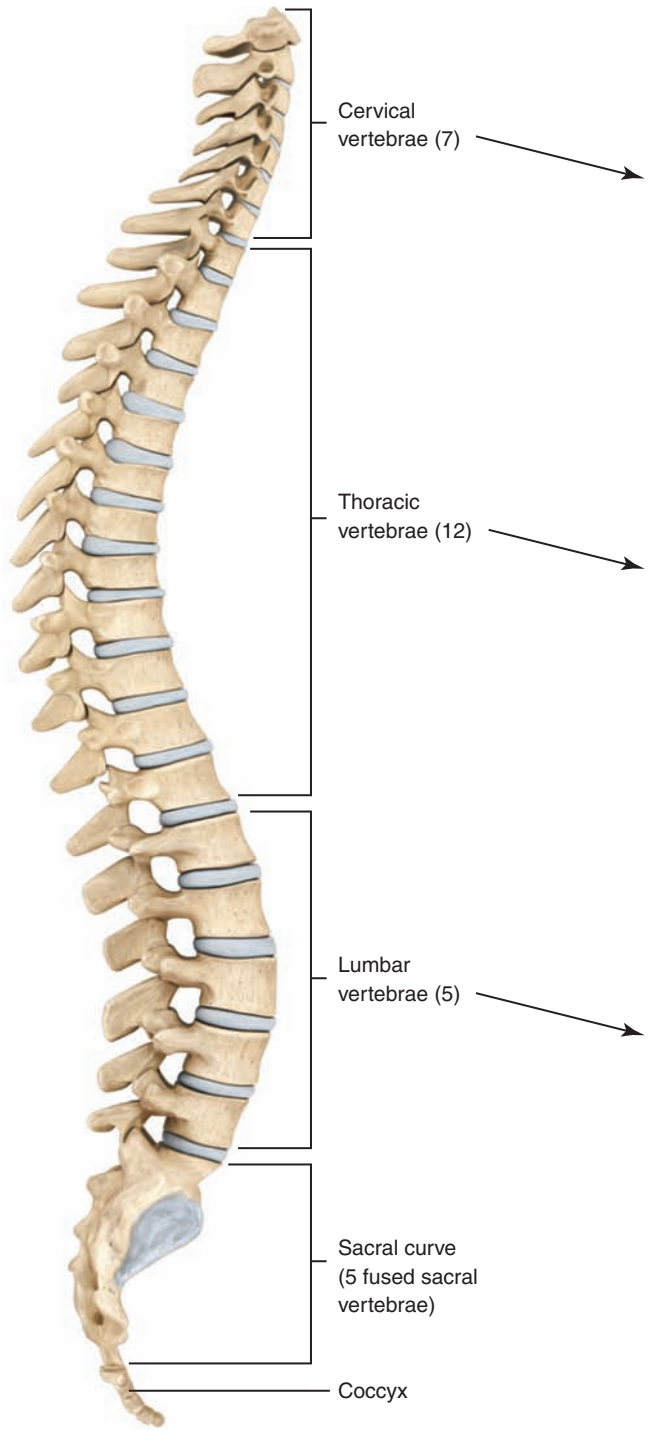
Osteoporosis, a disease that causes progressive bone weakening, often attacks the axial skeleton. The disease results from an imbalance in bone homeostasis, making bones fragile and less able to support weight, and increasing the chance of fracture. Painful vertebral fractures can cause a "dowager's hump" that can reduce height by several inches. Osteoporosis causes an estimated 1.5 million fractures a year in the United States alone. Hip fractures, largely due to osteoporosis, are a major cause of death, disability, and loss of independence among older people. **Osteopenia**, a condition of low bone density thought to be a precursor of osteoporosis, affects some 30 million women and 14 million men in the United States. Studies show that impact and muscular stress on bones (through exercise, such as weight lifting or running) helps mineralize bone, and fights both osteopenia and osteoporosis. These structures are visible in Figure 6.8.

Ribs attach to the thoracic vertebrae to form the thoracic cage.

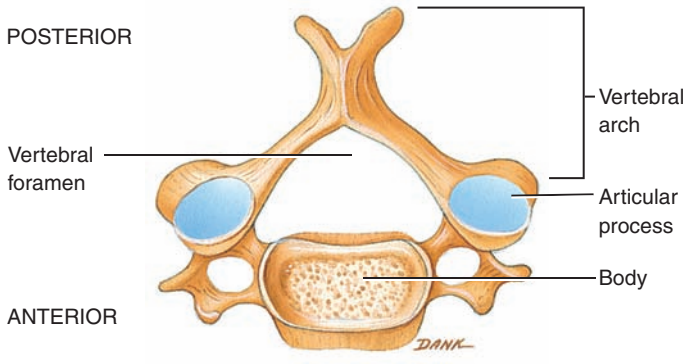
We have seven pairs of **true ribs** and five pairs of **false ribs**. The true ribs attach directly to the sternum or make a direct connection with the costal

The vertebral column and vertebrae • Figure 6.8

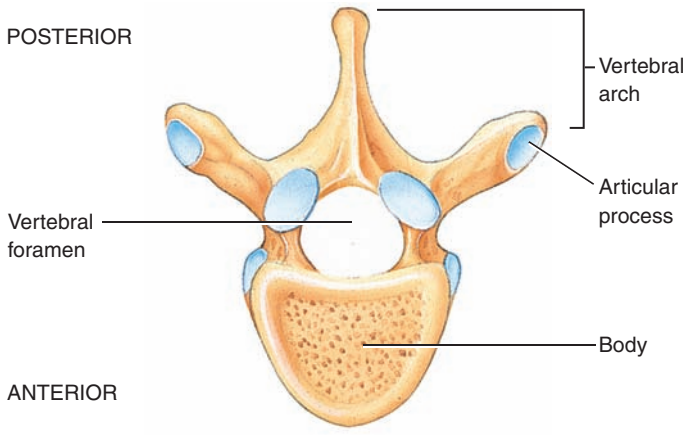
The parts of the vertebra include the vertebral body, the spinous process (the bumps that run down the middle of your back), the articulating surfaces that connect one vertebra to the next in your spinal column, and the vertebral foramen where the spinal cord lies. Cervical vertebrae are thinner and more delicate than the rest of the vertebrae. Thoracic vertebrae each articulate with a rib. Lumbar vertebrae have heavy bodies capable of supporting the weight of the torso.



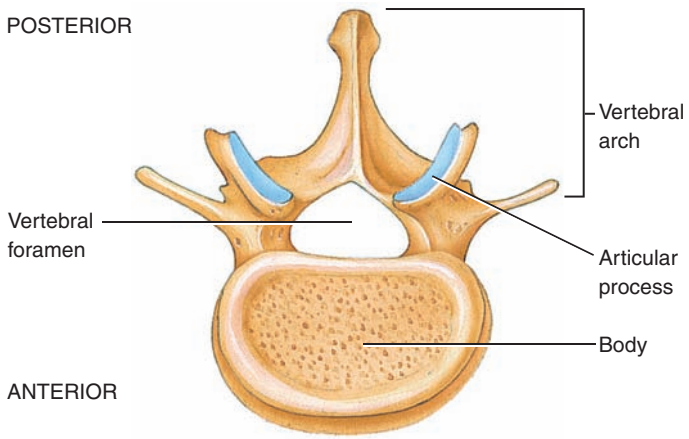
a. Vertebral column (lateral view)



b. Superior view of cervical vertebra



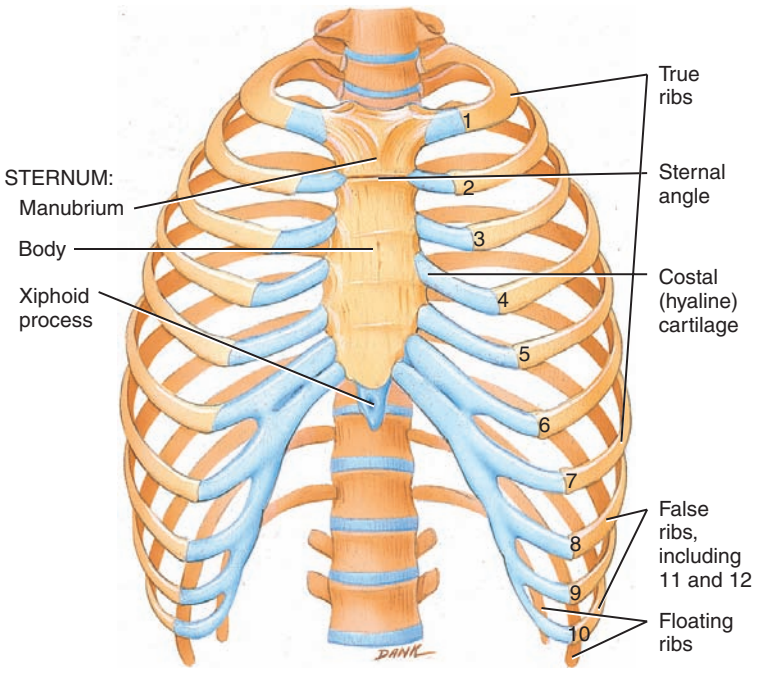
c. Superior view of thoracic vertebra



d. Superior view of lumbar vertebra

Thoracic cage • Figure 6.9

The thoracic cage is composed of ribs and sternum (shown in beige) and cartilage (shown in blue).



Anterior view of skeleton of thorax

(rib) cartilage, which in turn is directly associated with the sternum. False ribs either attach to the costal cartilage (ribs 8, 9, and 10), which then joins the sternum, or are free at their lateral ends (sometimes called floating ribs 11 and 12). Despite what you may have heard, males and females have the same number of ribs. See Figure 6.9 for details of the bones in the thoracic cage.

The sternum, or breastbone, protects the anterior of the chest. The three parts of the sternum are the **manubrium**, which articulates with the appendicular skeleton; the **body**; and a small tab of cartilage at the end of the body, the **xiphoid process**. The diaphragm and rectus abdominus muscles (the six-pack muscles so dramatically featured in bodybuilding magazines) attach to the xyphoid process. If you take a CPR course, you will be trained to locate the xyphoid process and avoid it as you depress the chest wall. Force can easily break the xyphoid process from the sternum, piercing the liver and causing life-threatening internal bleeding. This is NOT ideal if you want to save that life!

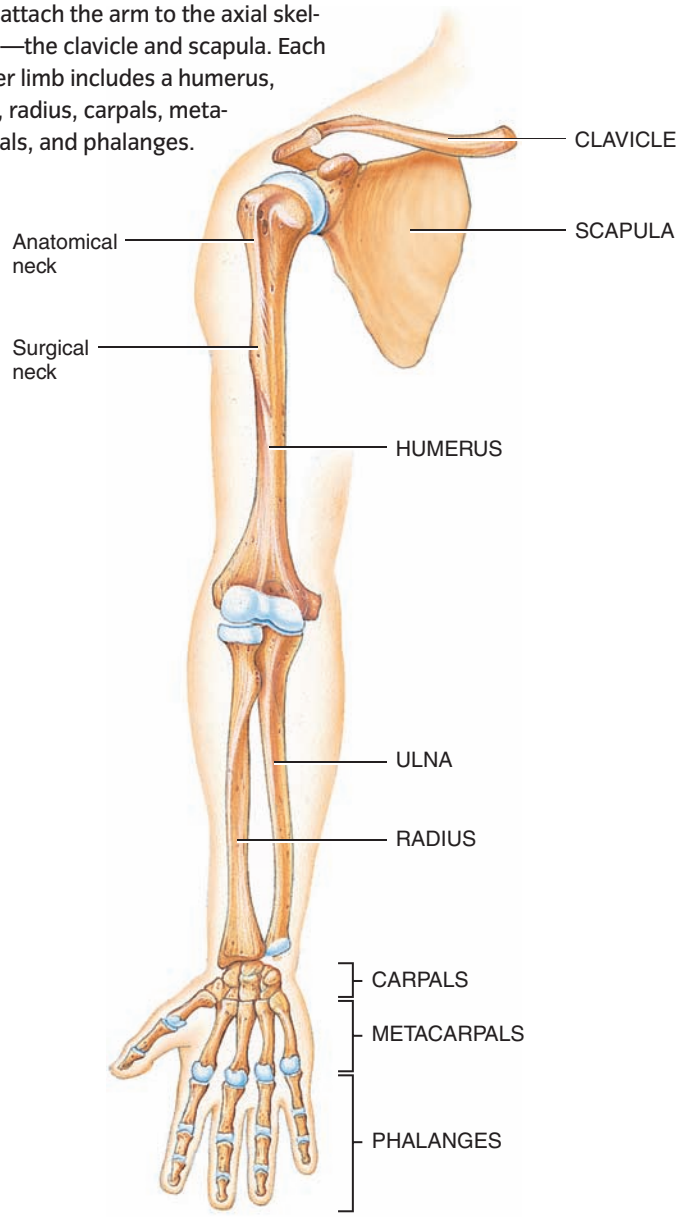
Your Limbs Comprise Your Appendicular Skeleton

The appendicular skeleton includes all the bones that are attached, or appended, to the axial skeleton. Specifically, it includes the **pectoral girdle**, the upper appendages (arms and hands), the pelvic girdle, and the lower appendages (legs and feet). All of the bones of the pectoral girdle and upper limb can be seen in Figure 6.10.

pectoral girdle The bones that attach the arm to the axial skeleton; the shoulder bones.

Pectoral girdle and right upper limb • Figure 6.10

The pectoral girdle consists of the bones that attach the arm to the axial skeleton—the clavicle and scapula. Each upper limb includes a humerus, ulna, radius, carpals, metacarpals, and phalanges.



Anterior view

The pectoral girdle connects the arm to the axial skeleton. Our bodies have two pectoral girdles, each consisting of a clavicle and scapula. The clavicle is the bone that most commonly breaks in car or bicycle accidents. To stop their fall, most people naturally respond by using their hands for protection, which transfers the shock of landing up the strong arm bones, concentrating it on the **clavicle**. This pressure is generally opposite the strong axis of the clavicle, which breaks the bone.

The **scapulae** (singular: *scapula*) are the "chicken wings" on your back. These bones connect to the strong back muscles and articulate only with the clavicles, which gives each shoulder joint its range of motion.

The **humerus** is the longest and strongest bone in the upper appendicular skeleton. The anatomical neck of the humerus is actually quite thick and strong. The surgical neck is the thinner area of the humerus distal to the neck, where the musculature of the arm does not cover the humerus well. You can feel this area by running your hand approximately one-third of the way down the arm, until you feel your unprotected bone. Most breaks to the humerus occur at the surgical neck rather than the anatomical neck.

Distal to the humerus is a pair of bones in an area commonly known as the forearm. The **ulna** is on the medial side of the forearm, the same side as your little finger, and is the longer of the two bones. The **radius** is on the thumb side of the forearm. One way to learn this arrangement is to memorize the mnemonic "p.u." (the **p**inky is on the **u**lna side). The *elbow* is the joint formed by the distal end of the humerus and the proximal ends of the radius and ulna; a large projection of the ulna called the *olecranon* forms the point of the elbow. At the other end of the forearm, the radius is in more direct contact with the next set of upper limb bones, the carpals.

The wrist bones (**carpals**) are in two rows of four short bones. The **metacarpals** make up the structure of the hand. If you make a fist, the distal tips of the metacarpals are those protruding knuckles. A "boxer's fracture" is a shearing of the distal end of a metacarpal, which makes the knuckle recede.

The **phalanges**—finger bones—are considered long bones. Each finger has three bones: the proximal, middle, and distal phalanx. The thumb (pollex) has only two phalanges. With excessive writing, a small sesamoid bone can develop in the tendon of the thumb because the tendon rubs over the joint between the proximal phalanx and metacarpal.

The pelvic girdle connects the lower limbs to the axial skeleton. In the anatomical position, the phalanges of the hand reach below the beginning of the lower limb. The lower limb, or leg, originates at the pelvic girdle. The bones of the pelvic girdle and the lower limb are presented in **Figure 6.11** on the next page. This girdle, composed of the hipbones and lower vertebrae, is much denser, stronger, and less flexible than the appendicular girdle. The hipbone emerges from three bones that fuse in early puberty: the ilium, ischium, and pubic bone. The femur articulates at the junction of these three bones. The **acetabulum** is the curved recess that serves as a socket for the head of the femur.

The pelvis is technically made of two large coxal bones (hipbones) that make up the pelvic girdle, plus the sacrum and the coccyx. This is shown in **Figure 6.11a**. Between each of the two coxal bones is a pad of fibrocartilage called the symphysis pubis, which serves the same purpose as the intervertebral discs. Each coxal bone articulates posteriorly with the sacrum. The sacroiliac joint, made famous by a comedy team from vaudeville and early television called the Three Stooges ("Oh, my aching sacroiliac!"), lies between the sacrum and the ilium.

Male and female hipbones are visibly different. Female hipbones are shallower, broader, and more dished, and have an enlarged pelvic outlet, a wider, more circular pelvic inlet, and a broader pubic angle. Each of these modifications eases childbirth by enlarging or smoothing the portion of the birth canal in the pelvis. Unfortunately, these modifications also change the angle of attachment of the female femur. This slight shift alters the position of the knee joint, leading to a knock-kneed appearance and increasing the chance of knee and ankle injuries among women athletes.

The femur is the longest and heaviest bone of the body. A ligament lies inside the hip joint capsule and connects the head of the femur to the acetabulum. This is the only ligament that lies completely within a joint—perhaps it is there to improve stability. The connection between hip and femur are depicted in **Figure 6.11b**. The neck of the femur joins the shaft at a 125° angle, putting huge stress on the neck. This arrangement makes the femoral neck susceptible to breaking as bones thin and weaken with age. A total hip replacement is a surgical procedure that replaces the head of the femur, the femoral neck, and a portion of the femoral shaft with metal parts.

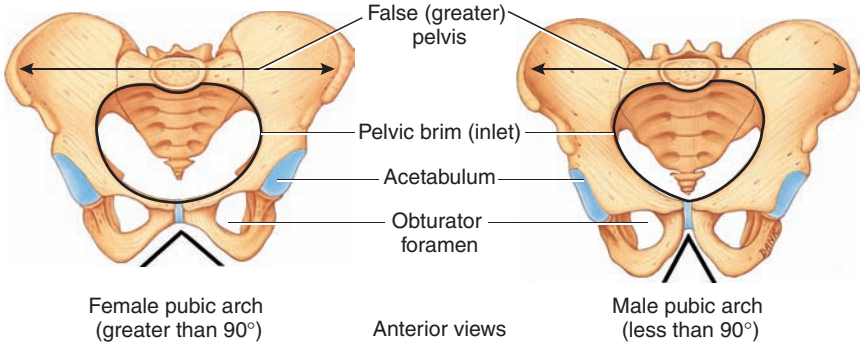
The kneecap is counted as a bone. The patella, or kneecap, forms within the tendon of the quadriceps femoris, the powerful muscle that straightens the knee. Interestingly, although the patella is counted among the 206 bones, humans are not born with a bony patella. Instead, they are born with a cartilaginous blob for a kneecap. The final structure of the patella is visible in **Figure 6.11c**. These bones provide flexible strength for movement, strength that can be recreated in those without proper bone formation. See *Ethics and Issues: Reinventing the Skeleto-Muscular System* for a discussion of this.

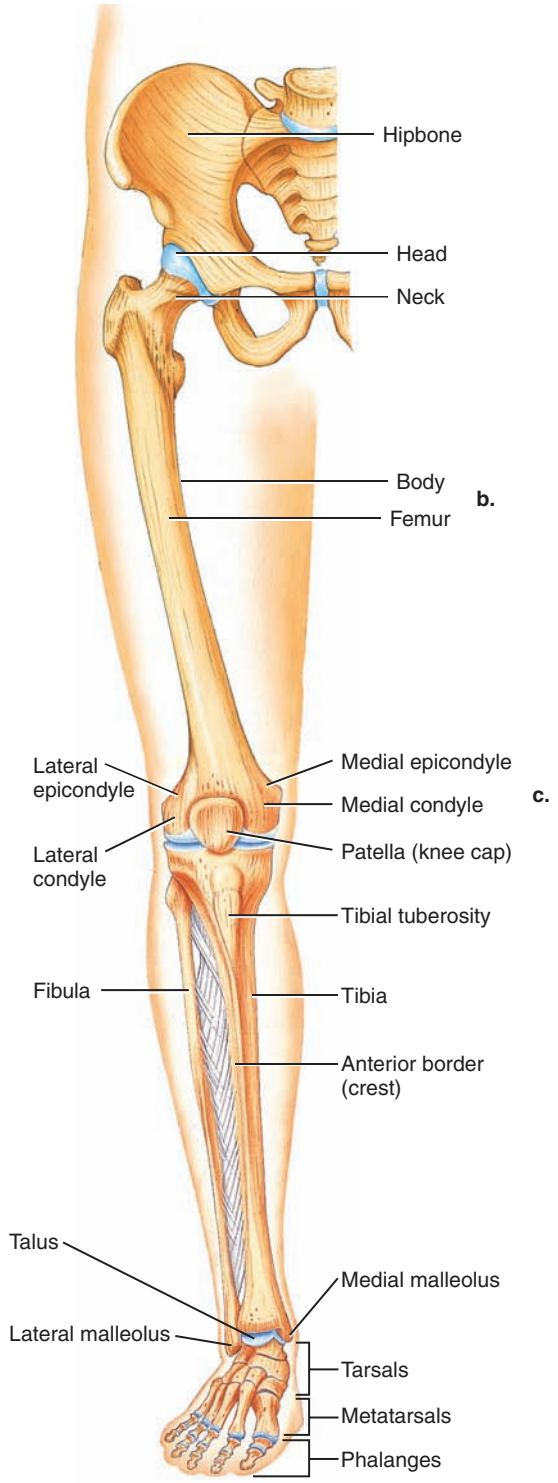
Joints Link the Skeletal System Together

The skeletal system provides internal scaffolding from which the skin, muscles, and organs are suspended. The skeleton, however, must not only support and protect, but also flex and move. This task is accomplished by the joints of the body, which exist wherever two bones meet. These joints can be classified by function or by structure. Functionally, joints are:

- immovable or **synarthrotic**
- semimovable or **amphiarthrotic**
- freely movable or **diarthrotic,** also called **synovial**

Structurally, a joint is considered a bony fusion, or a fibrous, cartilaginous, or synovial joint. The term *synovial* is confusing, however, because it describes both the fluid in the joint (structure) and any structure that secretes synovial fluid (function).





Pelvic girdle and right lower limb • Figure 6.11

Skeletal gender differences become obvious when comparing male and female pelvic girdles (part a). The bones of the leg include the heavy and strong femur and tibia as well as the more delicate fibula.

ETHICS AND ISSUES

Reinventing the Skeleto-Muscular System

In the spring of 2008, the Court of Arbitration for Sport told Oscar Pistorius that he could compete in the 2008 Olympic Games. Because he was born without fibulas, Pistorius's lower legs were amputated when he was 11 months old. His lower legs have been fitted with J-shaped carbon-fiber blades (called the "Cheetah Flex Foot" because it is based on a cheetah's hind leg), as shown in the photograph. Prior to the Pistorius ruling, runners who use high-tech graphite "blades" had been restricted to competing in the World Paralympic Games. The "bladerunners" were thought to have a mechanical advantage over other runners, since one experiment showed that the blades allowed them to use 25% less energy and do 30% less mechanical work lifting their bodies as they ran. A researcher at the Massachusetts Institute of Technology disagreed with these findings and conducted experiments showing that bladerunners do not have an unfair advantage. The Court of Arbitration used that evidence in making its ruling. Others argued that Pistorius's world-class speed is due to the skeleto-muscular power generated by his upper legs, not to his Cheetahs.

While world-class athletes create headlines, improvements in artificial-leg technology becoming available today and in the next few years may help millions of people get out of wheelchairs or put down their crutches and canes. The vast majority of people who require foot or leg amputations suffer from diseases, such as diabetes. Most are over 50, and many have multiple health complications. They require technology that is lightweight, allows them a maximum range of motion, provides a "normal" feel, and doesn't take a lot of learning or practice to get used to.

Doctors believe the ability to walk more naturally provides these people with a variety of health benefits and reduces the societal cost of their medical care. Getting more people on their feet again can even reduce the amount of greenhouse gas and pollution caused by the need for handicap-access vans and the large, bulky batteries used on motorized wheelchairs.

Above-knee prosthetics allow for the knee joint to be programmed for up to 10 different activities, from walking to running, bicycling, and driving. The knee mode can be changed with a simple click of a remote control like the one used for a garage door or television. Older microprocessor-based prosthetic legs can be programmed for only two modes and must be reprogrammed for specialized uses.

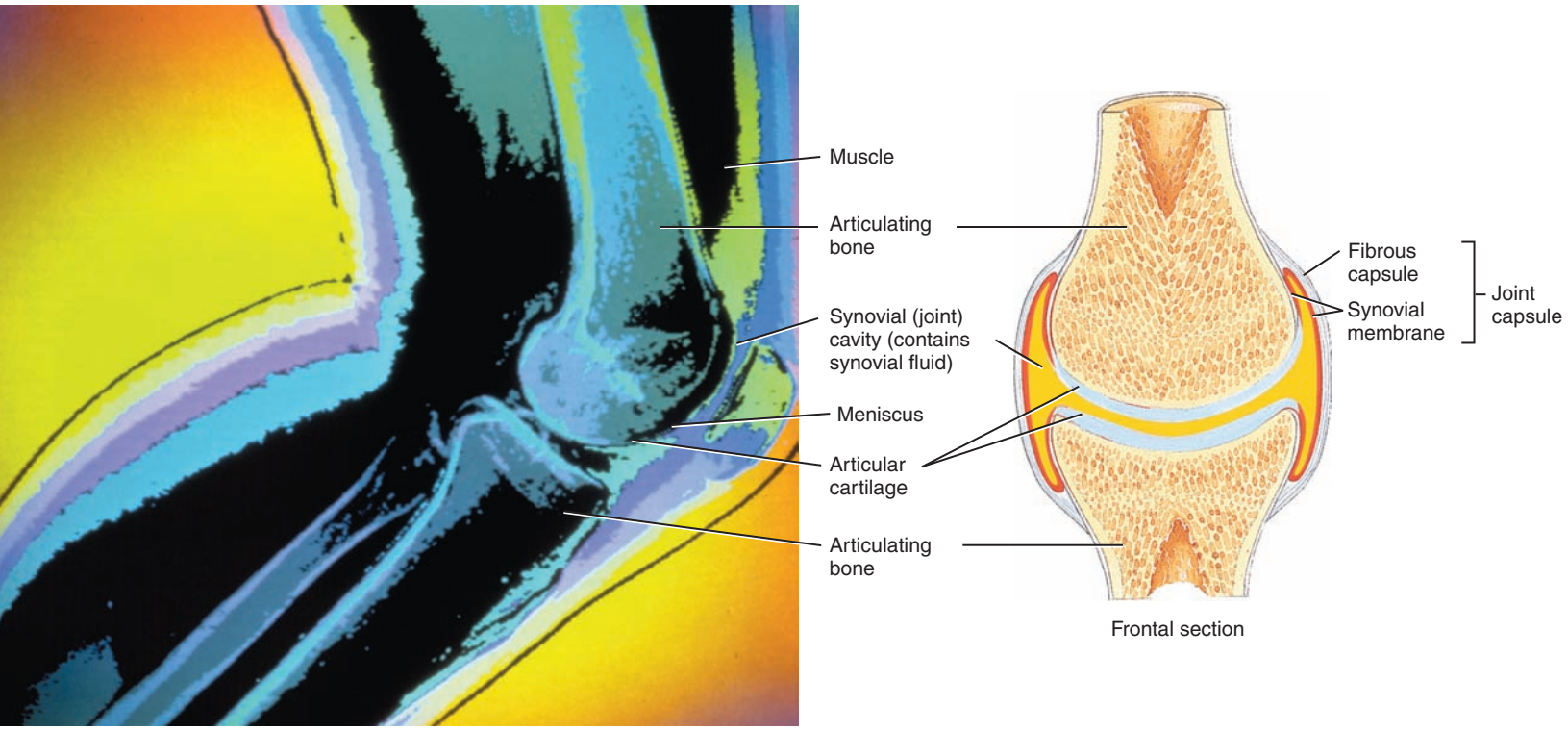
New-generation microprocessor-based prosthetics are more sensitive to changes in movement. Legs adjust speed and gait more fluidly than before, and arms twist to perform complex tasks without as much conscious effort on the part of the user. As a result, a person can walk slow or fast and even jog, or grip a steering wheel, lift groceries, and open a house door.

Critical Reasoning Issues Of course, all of this has costs. Current microprocessor-based prosthetic legs cost approximately $30,000 each, and new ones may be more expensive. The military is spending millions of dollars on high-tech artificial-limb research.

Think Critically

1. Will high-tech limbs and carbon-fiber racing blades create a world of prosthetic haves and have-nots? Should more money be spent providing simpler, but useful, artificial limbs to the millions of people around the world who lose limbs each year to disease and injury, not to mention landmines and cluster bomb remnants from past wars in their countries?
2. In the Pistorius case, those who were against his inclusion in non-handicapped competition argued that allowing him to race would be the first step down a "slippery slope" leading to a situation in which all runners try to gain some sort of mechanical advantage. Do you think this might happen?

A synovial joint—the knee • Figure 6.12



Synovial joints are the most common kind, and allow free movement between two bones. These joints serve as the fulcrum of a lever, so the force generated by contracting muscle can move a load. A synovial joint is characterized by a complex joint structure bounded by a joint capsule containing **synovial fluid**. Tendons, ligaments, **bursae** (singular: *bursa*), and **menisci** (singular: *meniscus*) are often associated with synovial joints. Accessory ligaments outside the joint help to stabilize and reinforce the joint capsule. A typical synovial joint is presented in **Figure 6.12**. Some joints, like the hip and shoulder, have ligaments inside the joint capsule. In the knee, the **anterior** and **posterior cruciate ligaments** are inside the joint capsule.

synovial fluid Fluid secreted by the inner membrane of a synovial joint, similar in viscosity to egg white.

bursa Fluid-filled sac between the bones or tendons of a joint and the skin, positioned to reduce friction.

menisci Fat pads within joints that cushion bones and assist in "fit."

When a joint moves, so do the overlying tissues. To reduce friction and absorb shock from this movement, fluid-filled sacs called bursae are found in the connective tissue surrounding many joints. These sacs can be damaged, resulting in inflammation of the bursae. Bursitis, as this is called, is usually attributed to severe, repetitive motion at a joint.

Another supportive structure associated with synovial joints is a meniscus, or fat pad. This structure can improve the "fit" between the bones and the joint capsule. For example, the medial and lateral menisci of the knee help stabilize the knee and provide lateral support. These menisci are commonly injured in side impacts in games, such as football and rugby.

CONCEPT CHECK

1. **What** are the divisions of the skeletal system?
2. **Which** bone is strong with a slight anterior curve to bear the weight of the upper torso?
3. **How** are the pectoral and pelvic girdles similar? **How** are they different?
4. **What** are the different types of joints and the movements provided by each?

6.4 Skeletal Muscles Exercise Power

LEARNING OBJECTIVES

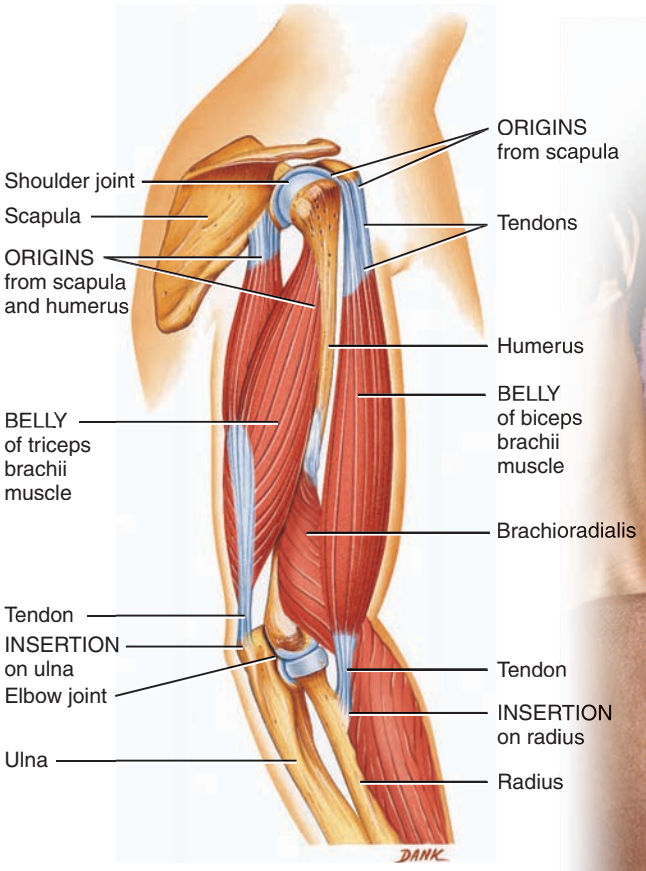
1. **Describe** the anatomy of a skeletal muscle.
2. **Diagram** the arrangement of proteins in the sarcomere.
3. **Describe** the appearance of the neuromuscular junction.
4. **Outline** the steps in the sliding filament model.

Muscular tissue is contractile tissue. Studies of the muscular system usually focus on **skeletal muscle** and its connective-tissue covering. The human body has two other types of muscle tissue—cardiac muscle (Chapter 12) and smooth muscle—that are not found in the skeletal muscles.

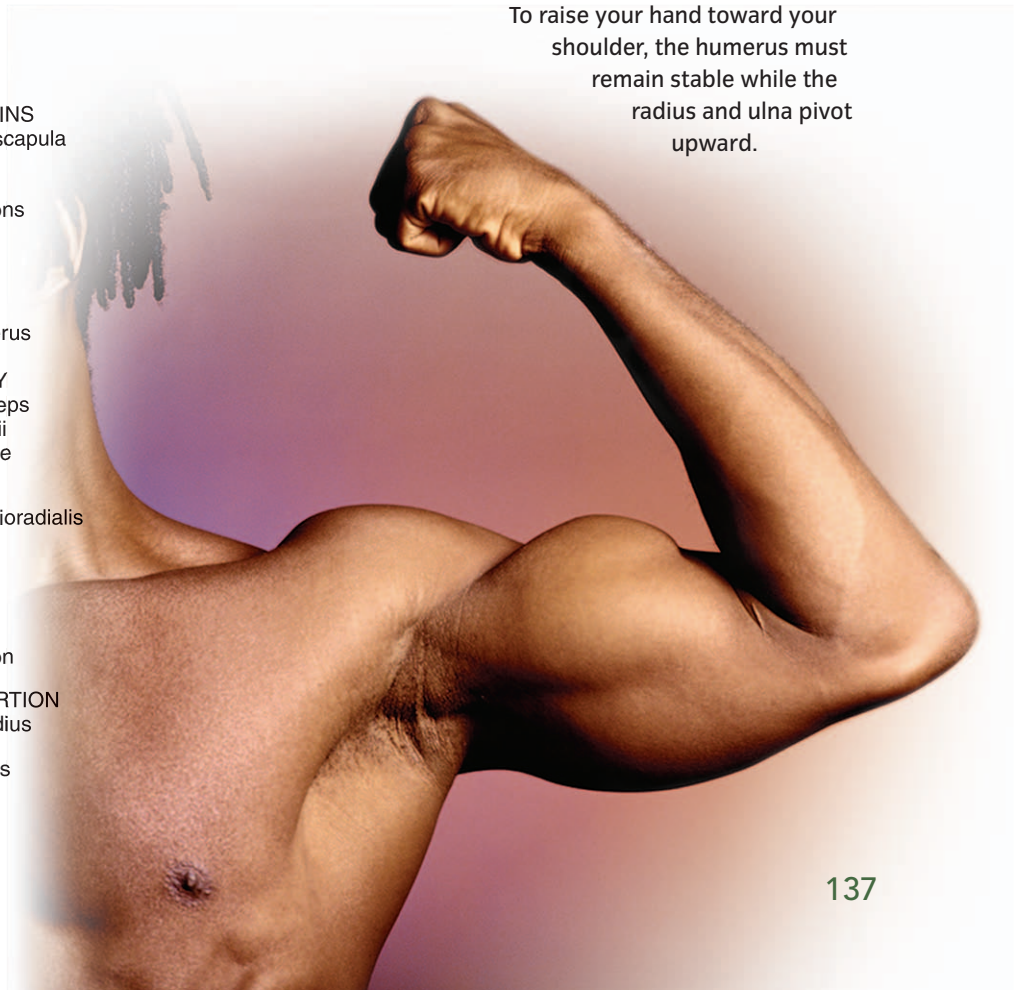
skeletal muscle
Contractile tissue composed of protein filaments arranged to move the skeletal system.

In general, each skeletal muscle has an **origin**, an end that remains stationary when the organ shortens, and an **insertion**, an end that moves during contraction. Knowing the origin and insertion of any skeletal muscle offers clues about its function. If you mentally pull the insertion toward the origin, you can visualize the effect of contraction. For example, to raise your hand toward your shoulder, the main long bone of the arm, the humerus, must remain stable while the bones of the forearm, the radius and ulna, pivot upward. This movement is accomplished by contraction of two muscles, the brachialis and biceps brachii muscles. The origin for the brachialis is at the upper end of the humerus, and the insertion is at the proximal end of the ulna. When the brachialis muscle contracts, the humerus remains stationary and the ulna moves toward it. The origin for the biceps brachii is on the shoulder blade or scapula, and its insertion is on the radius. When this muscle contracts, the scapula above the humerus remains in place and the radius moves upward to meet it. See **Figure 6.13**.

Movement: muscle origin and insertion • Figure 6.13



Origin and insertion of a skeletal muscle

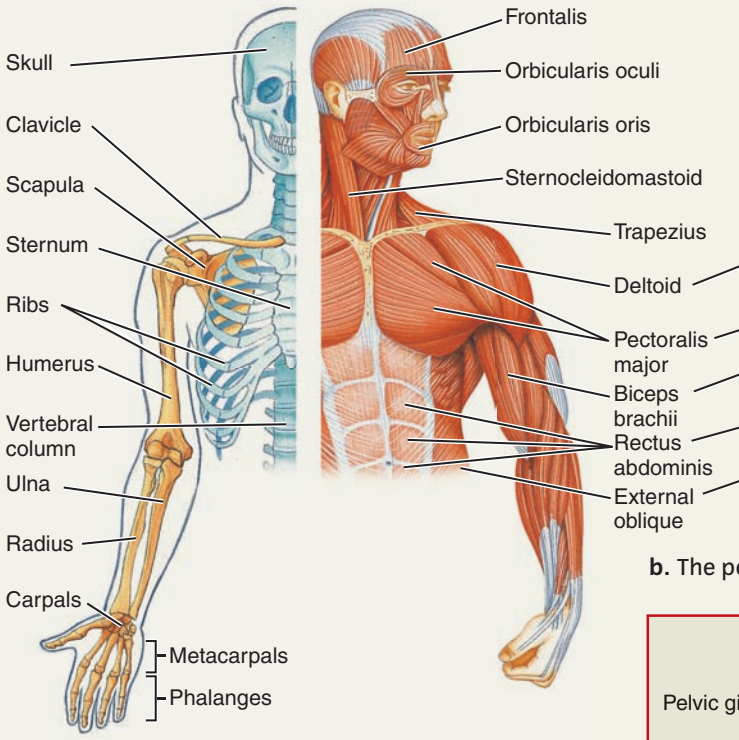


Just as the skeleton and muscles work together to produce fluid movement, so too do the muscles themselves. To coordinate and control body movements, most human skeletal muscles function as a member of an **antagonistic** or **synergistic pair**. One or more muscles provide movement (the **prime mover** or **agonist**) while a second muscle or group opposes that movement (the **antagonist**). Moving your hand to your shoulder requires the simultaneous contraction of the prime movers, the brachialis and biceps brachii muscles, and relaxation of

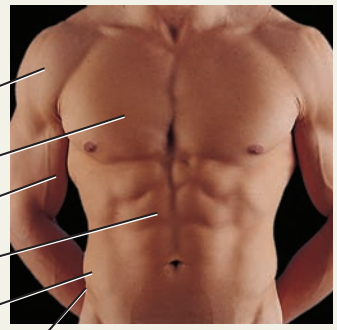
antagonistic (synergistic) pair Muscles with opposing actions working together to provide smooth and controlled movements.

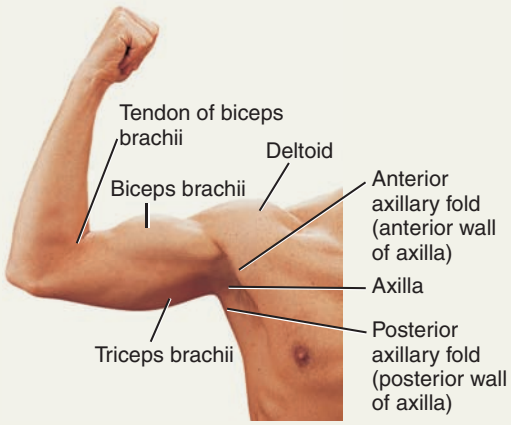
Biological InSight

Skeleto-muscular systems • Figure 6.14

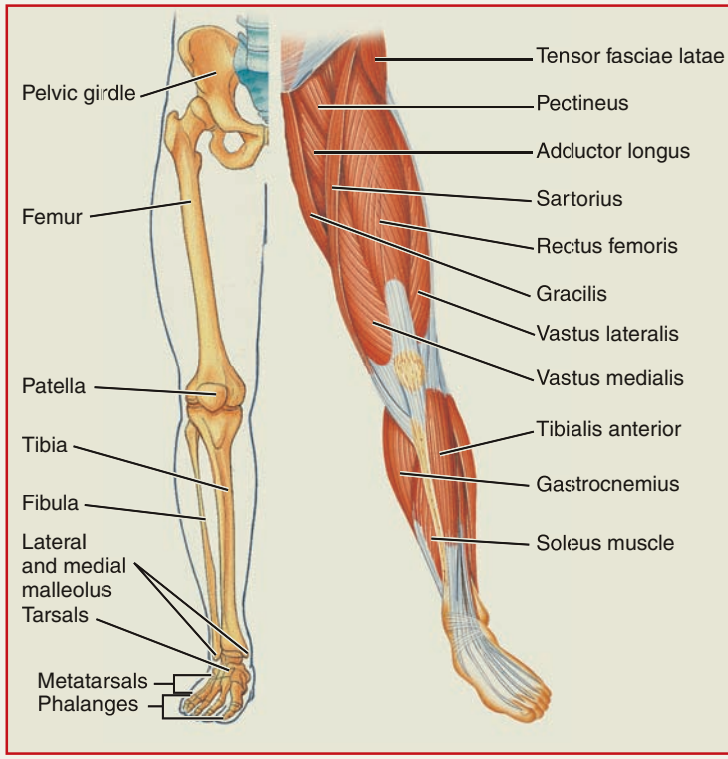


a. The head, thorax, pectoral girdle, and arm





b. The pelvic girdle and legs



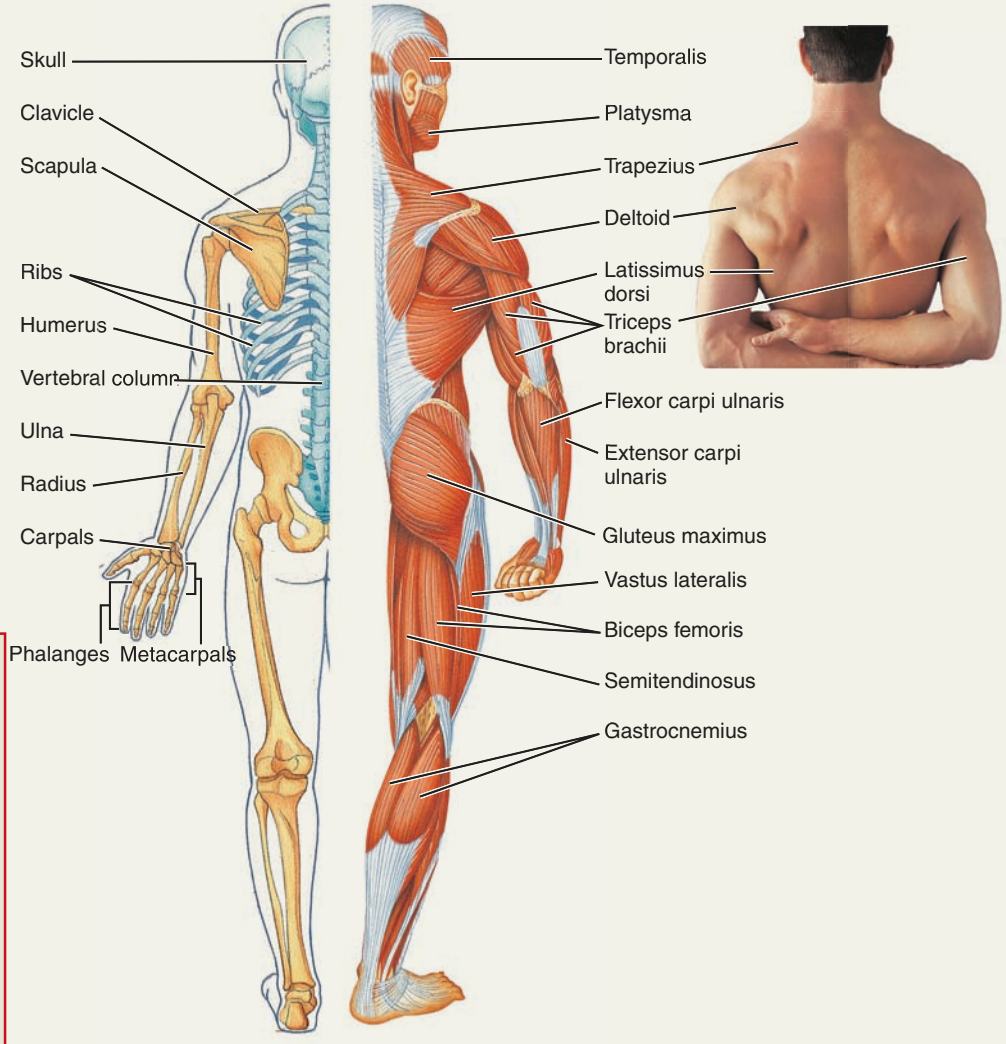
the antagonist, the triceps brachii. These muscle pairs can often be identified by simply looking carefully at the superficial muscles. Occasionally, the prime mover will be on the anterior surface and the antagonist will be on the posterior surface. The major superficial muscles of the body are identified in **Figure 6.14**.

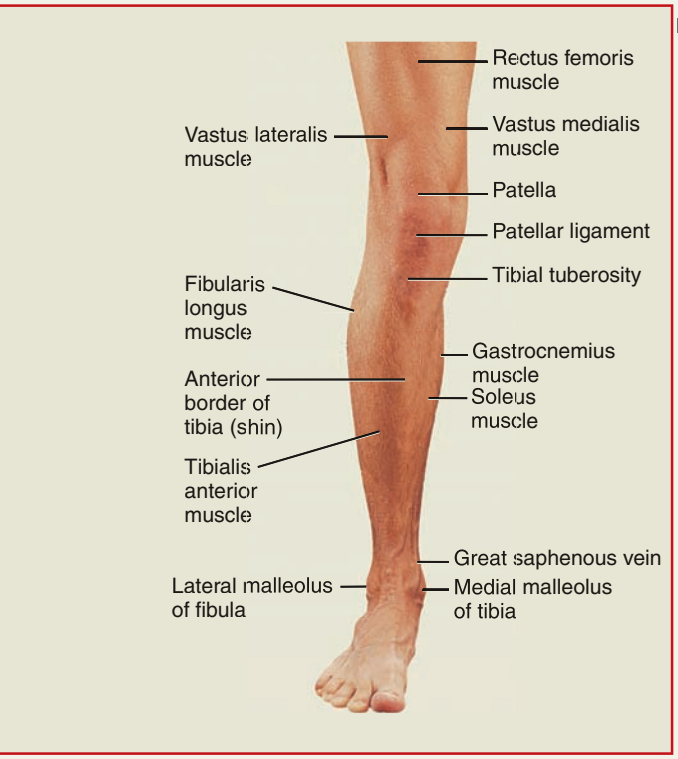
Skeletal Muscle Is Built Like Telephone Cable

Skeletal muscles are beautiful, simple organs with an awe-inspiring degree of organization. When we look closely, we see an amazingly effective internal configuration that shows how repetition and small forces, properly organized

THE PLANNER

c. The body's posterior





and coordinated, can produce strength and beauty. If you cut through the center of a skeletal muscle, you will see an internal structure that resembles a telephone cable. Skeletal muscle is composed of numerous elongated structures, running from origin to insertion, one nested inside another. See **Figure 6.15**.

Individual skeletal muscle cells are long—sometimes 30 centimeters (or even longer in the sartorius muscle of the thigh). Muscle cells are also quite slender and exceedingly fragile. These long, fragile cells must shorten, creating tension. Without connective tissue support, the soft tissue of the muscle cell would not be able to withstand the tension needed to provide movement, and the cell would rip itself apart rather than shorten the organ. In a telephone cable, individual wires are coated with insulation and then grouped in small units within a larger cable. Similarly, skeletal muscle is grouped into individually protected cells, held together in fascicles, and then grouped to form the entire organ. This "nested fibers" arrangement extends to the microscopic organization of skeletal muscle tissue. Look at a single muscle cell, or **myofiber**, and you will see an even smaller level of elongated, nested fibers.

The muscle cell itself is covered in a cell membrane very much like that discussed in Chapter 4. In this case it is called a **sarcolemma**, and it has specialized areas, **T tubules**, that conduct the contraction message. Inside the sarcolemma is a parallel series of **myofibrils**.

T tubules Tubes formed in the sarcolemma that cross through the muscle cell, carrying contractile impulses to all parts of the muscle cell.

myofibrils Linearly arranged groups of the contractile proteins actin and myosin.

Proteins Drive Muscles

Inside these myofibrils, we find one final level of nested, elongated structures—microfilaments composed of the proteins **actin** and **myosin**. These two microscopic proteins interact in a way that causes the entire muscle tissue to shorten and therefore produce movement.

If you interweave the fingers of both hands and slide them together, you can approximate the interaction of actin and myosin. These proteins are held in regular arrangements in contractile units, or **sarcomeres**, that are stacked end to end in the myofibrils. Although each sarcomere is quite small, when they all contract at once, the force generated is large enough to tap your toe or leap tall buildings in a single bound. Every one of our body movements originates in the interaction of these tiny proteins within the highly organized skeletal muscle: blinking, shoveling snow, playing the piano, or bench-pressing 200 kilograms.

The Sarcomere Is Built for Contraction

If you examine a sarcomere, you'll get clues to the nature of muscular contraction. Bands are visible in individual sarcomeres. All of the sarcomeres, and consequently their bands, line up within the muscle cell, visible as continuous dark and light areas on the cell. This alignment of sarcomeres and banded appearance produces striations in the muscle cell as a whole. We refer to skeletal muscle as striated tissue. The ends of the sarcomere make thin dark lines, called Z discs, that run transverse to the length of the muscle cell (think, "Z is the end of the alphabet and Z is the end of the sarcomere"). Attached to the Z discs, and extending toward the middle of the sarcomere on each side, are thin actin filaments. Thick myosin filaments are suspended in the center of the sarcomere between the actin filaments.

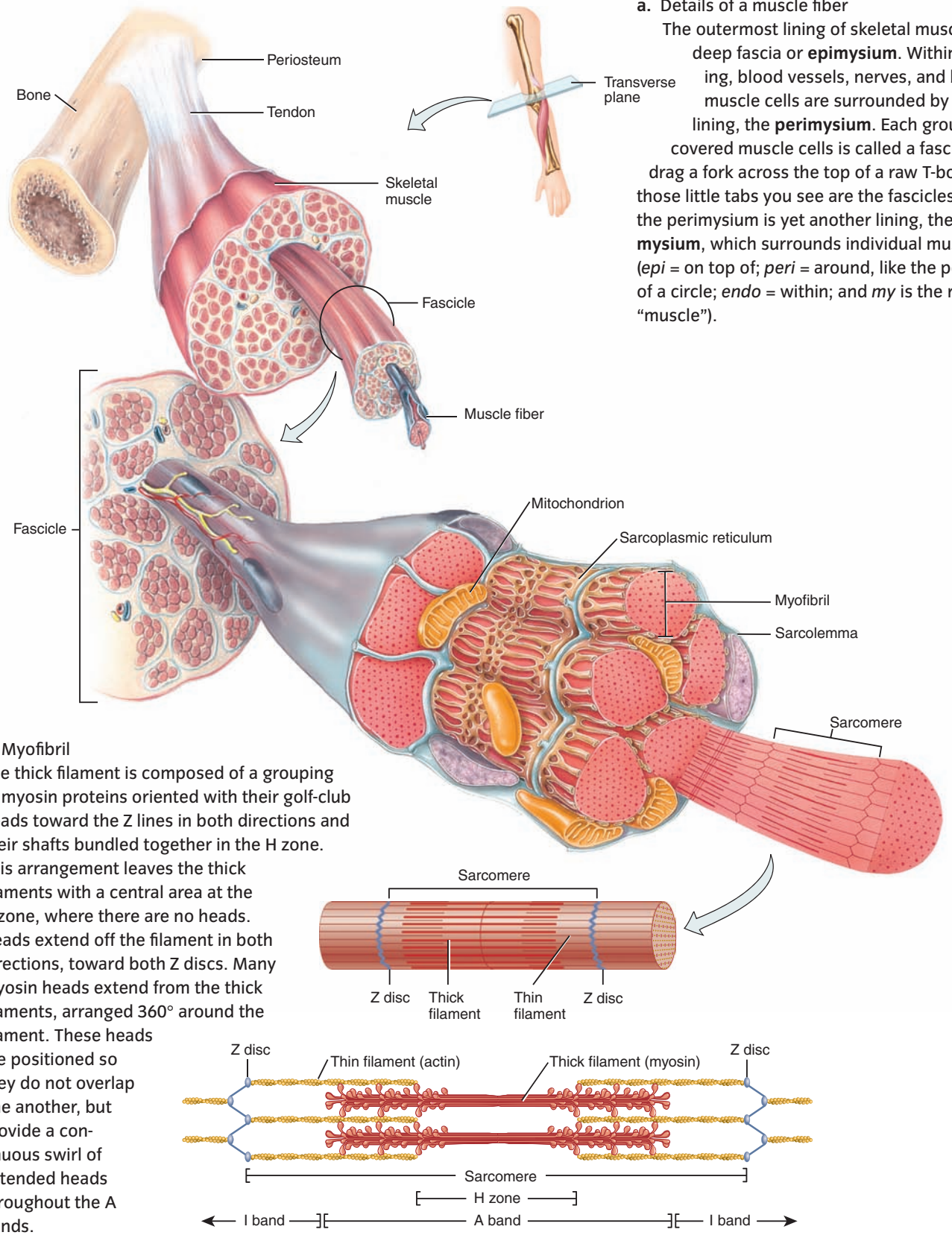
Passing light through a sarcomere reveals patterns of light and shadow due to the relative thickness of these structures. The bands in a sarcomere are named for their ability to block light. The **I bands** are between the Z disks and the myosin thick filaments, where only actin is found. These bands are light-colored because only the thin actin filaments are blocking the light ("I" stands for "isotropic," meaning light is not altered as it shines through). The portion of the sarcomere where myosin resides is thicker, so it blocks light, and is called the **A band**, which stands for anisotropic (*an* = without or against). In the center of the sarcomere, the **H zone** is a light portion where the thinner central sections of the myosin filaments are grouped and overlapping actin is absent. The H zone is important in contraction because it is the zone into which actin is pulled as the sarcomere contracts. The T tubules necessary for contraction are at the junction of the I bands and A bands in human skeletal muscle.

The contraction of skeletal muscle stems from the movement of actin (a globular protein) and myosin (a heavier, double-headed protein), as described in the **sliding filament model**. The use of the word "model" indicates that although we know quite a bit about the mechanics of sarcomere contraction, the picture emerging from research laboratories is continually refining that understanding.

Contraction Starts with a Nerve Impulse

Here the motor neuron ends very close to a group of muscle cells, separated only by a small, fluid-filled space called the **synapse**, or synaptic cleft.

Anatomy of a muscle • Figure 6.15



a. Details of a muscle fiber

The outermost lining of skeletal muscle is the deep fascia or **epimysium**. Within this lining, blood vessels, nerves, and bundles of muscle cells are surrounded by a second lining, the **perimysium**. Each group of covered muscle cells is called a fascicle. (If you drag a fork across the top of a raw T-bone steak, those little tabs you see are the fascicles.) Within the perimysium is yet another lining, the **endomysium**, which surrounds individual muscle cells (*epi* = on top of; *peri* = around, like the perimeter of a circle; *endo* = within; and *my* is the root for "muscle").

b. Myofibril

The thick filament is composed of a grouping of myosin proteins oriented with their golf-club heads toward the Z lines in both directions and their shafts bundled together in the H zone. This arrangement leaves the thick filaments with a central area at the H zone, where there are no heads. Heads extend off the filament in both directions, toward both Z discs. Many myosin heads extend from the thick filaments, arranged 360° around the filament. These heads are positioned so they do not overlap one another, but provide a continuous swirl of extended heads throughout the A bands.

c. Details of sarcomere

Nerves send a contraction impulse across the synapse via chemical messengers, called neurotransmitters. The most common of these messengers is **acetylcholine**, abbreviated **ACh**. When acetylcholine is released from the axon terminal, it diffuses across the synaptic cleft and binds to receptors on the surface of the muscle cell membrane, delivering the chemical signal to contract. This impulse to contract is then passed through the entire muscle cell via the T tubules.

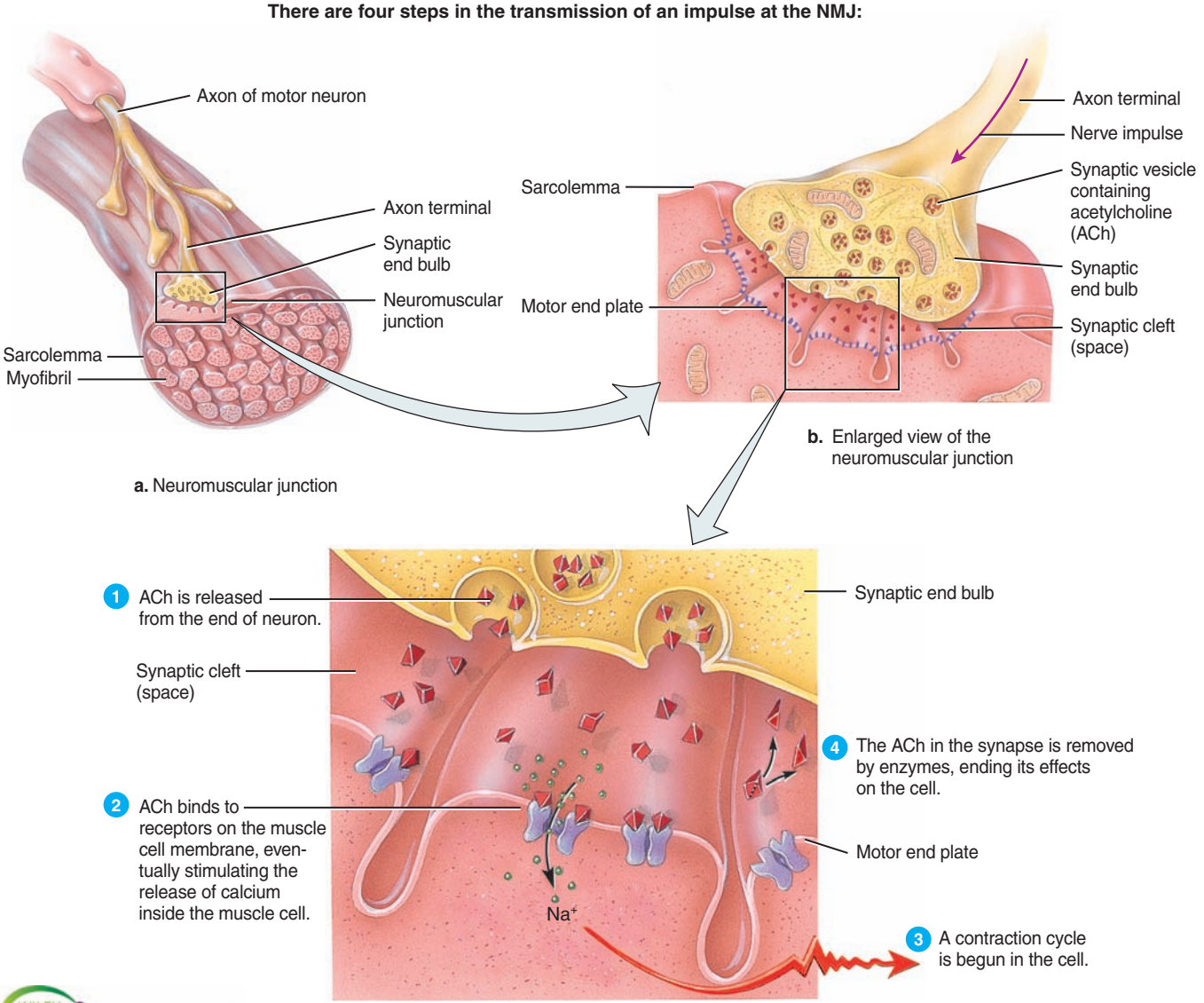
Inside the muscle cell is a particular organelle called the **sarcoplasmic reticulum (SR)**, which looks much like the endoplasmic reticulum discussed in Chapter 4. The sarcoplasmic reticulum stores calcium ions and releases them when acetylcholine binds to the surface of the cell. Calcium is held within the SR by a protein called calcium sequestrin. The storage and release of calcium from the SR is accomplished by an enzyme on the surface of the sarcoplasmic reticulum that removes calcium from the cytoplasm and moves it into the SR. This enzyme works by converting ATP to ADP, powering a calcium "pump." It may surprise you to learn that free calcium inside the cell is toxic. Removing excess calcium from the muscle cell cytosol and adding it to the inner chamber of the SR helps to ensure cell survival. An overview of this process is illustrated in Figure 6.16.

PROCESS DIAGRAM

Neuromuscular junction (NMJ) • Figure 6.16

THE PLANNER

There are four steps in the transmission of an impulse at the NMJ:

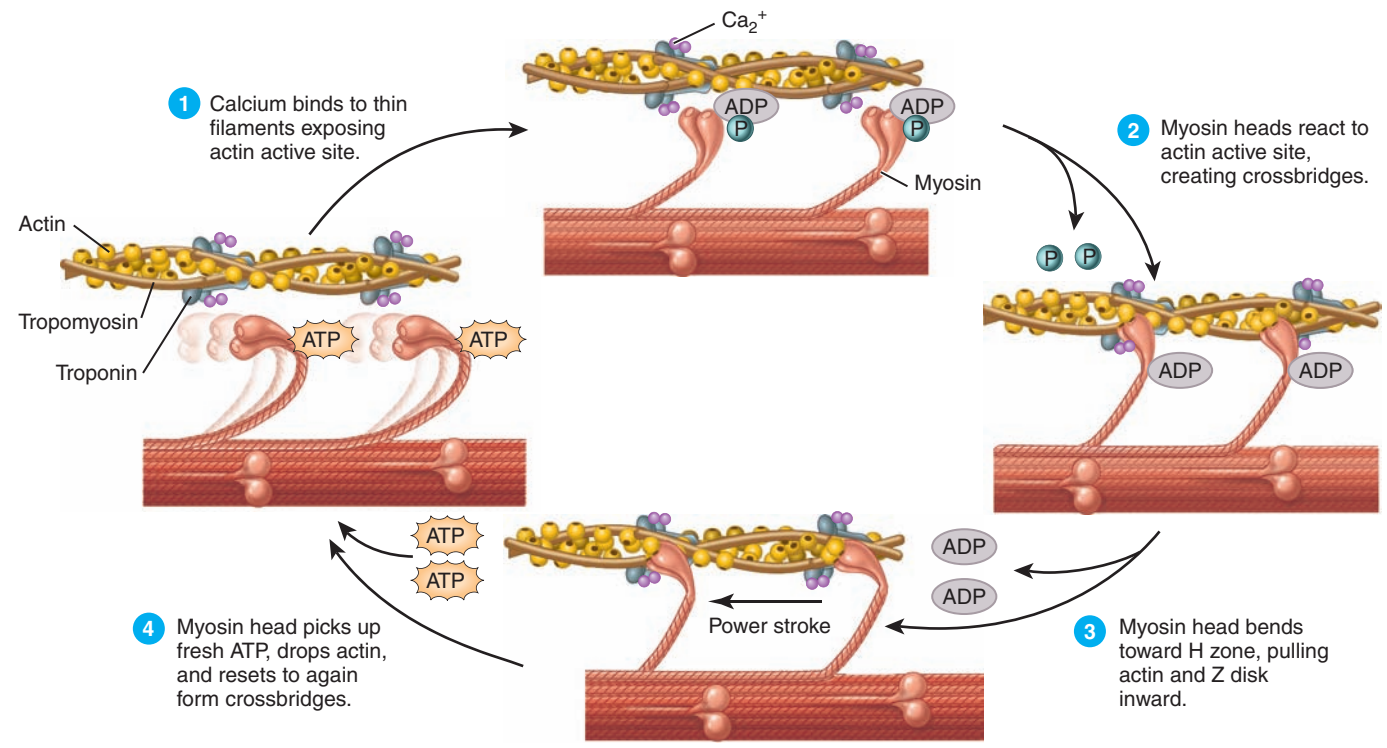


c. Binding of acetylcholine to ACh receptors in the motor end plate

WILEY PLUS Interactivity

Muscle contraction cycle • Figure 6.17

THE PLANNER



WILEY PLUS Interactivity

The Contraction Cycle Continues as Filaments Slide Past One Another

What happens next is a series of chemical reactions that proceed like a line of falling dominoes. The sliding filament model explains our best understanding of how muscle cells shorten. In this process, calcium initiates contraction, and proteins slide past one another, as shown in **Figure 6.17**.

Note that neither actin nor myosin undergoes any kind of chemical transformation, nor do they intertwine as the muscle cell contracts. Actin merely slides over the myosin filament, pulling the Z discs with it, hence the name "sliding filament model." This cycle of myosin grabbing exposed actin sites and ratcheting inward continues until (1) the removal of acetylcholine from the sarcolemma stimulates the return of calcium into the sarcoplasmic reticulum or (2) the supply of ATP is exhausted. Without a fresh supply of ATP, the myosin heads cannot release the actin molecule. (This is exactly what happens after death: rigor mortis sets in.)

If we zoom out from the microscopic scale, hundreds of simultaneous, asynchronous, ratchet-like movements pull the thin filaments of each individual sarcomere into the H zone. Because the thin filaments are attached to the Z discs, the Z discs are pulled along with the actin, shortening the sarcomere. With millions of sarcomeres lined up in each muscle cell, and many muscle cells innervated by one motor neuron, these tiny chemical reactions shorten the entire muscle.

CONCEPT CHECK

STOP

1. **What** is the anatomy of a skeletal muscle?
2. **Why** does skeletal muscle appear striated? Specifically, **what** is the underlying cause of those striations?
3. **What** does the neuromuscular junction look like?
4. **What** are the steps in the sliding filament model?

6.5 Whole-Muscle Contractions Require Energy

LEARNING OBJECTIVES

1. **Define** the all-or-nothing basis of muscle contraction.
2. **Explain** summation and tetanus.
3. **Compare** aerobic and anaerobic energy pathways.
4. **Describe** the different types of muscle fiber.

Knowing the biochemistry of contraction and muscle anatomy, we now have a good foundation for discussing whole-muscle contraction. How does an entire large muscle like that of your thigh contract and generate movement?

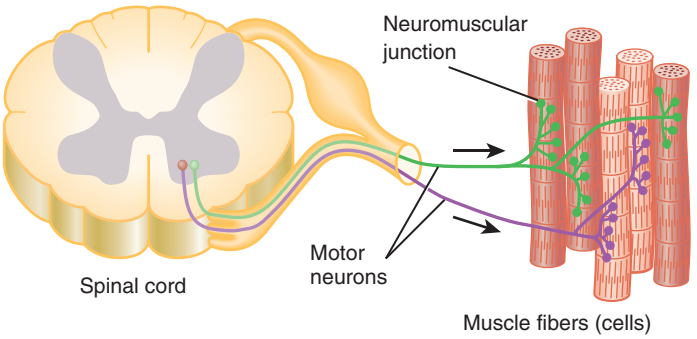
Muscle cells are grouped in **motor units**, composed of one motor neuron and the set of muscle cells it controls. Figure 6.18 illustrates a motor unit. Motor units vary in the number of muscle cells included; forceful contractions involve large motor units, while delicate movements require small precise motor units. The entire motor unit contracts when it receives a signal from the motor neuron. Muscle cells contract on an **all-or-nothing** basis. Nothing happens when the nerve stimulus is too weak to cause the release of calcium from the sarcoplasmic reticulum. In muscle cells, when the **threshold stimulus** is reached, calcium is released and the entire muscle cell contracts. **Graded contraction** is not possible at the cellular level. The all-or-nothing nature is similar to a mousetrap baited with cheese. A mouse can nibble the cheese and remove small amounts without consequence. However, as soon as the mouse removes enough cheese, the trap snaps shut, trapping the hungry rodent.

threshold stimulus The minimal amount of stimulation needed to cause a response.

graded contraction A smooth transition from a small, weak contraction to a forceful contraction.

Motor unit • Figure 6.18

Each motor unit is individually controlled. Contraction strength depends on how many motor units are stimulated. Few motor units are stimulated during a weak contraction, but feats of strength require many motor units.



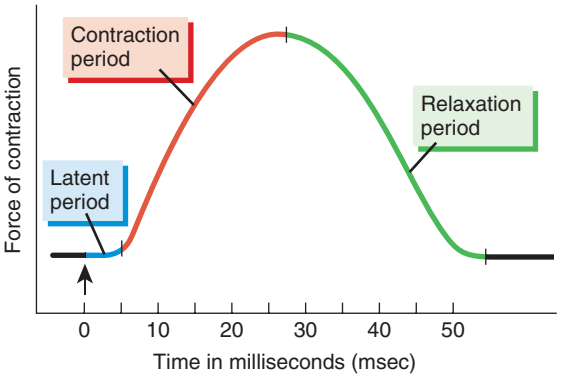
The Motor Unit Requires Multiple Stimuli

A myogram records a single contraction of one motor unit, called a single twitch. See Figure 6.19. Single twitches are not effective in producing body movement, because they last only a fraction of a second. To produce a meaningful amount of contraction, the motor unit requires multiple stimuli, reaching the muscle cell in such quick succession that it has no time to relax. Each contraction builds on the heels of the last, until the muscle cell is continuously contracted. This buildup of contractions is called **summation**. Once continuous contraction is achieved, the muscle is said to be in **tetanus**. (This continuous, and normal, contraction of the muscle is not the same as the bacterial infection also called tetanus.) The neck muscles of an adult are in tetanus most of the day. It is unusual to see adults' heads bobbing like a newborn's—unless they are trapped in a boring lecture!

Summation explains how single twitches can provide sustained movement, but how is the strength of contraction monitored and regulated? You know you are capable of graded contractions—you can pick up a pencil with ease, using the same muscles that you would use to pick up a big stack of weighty textbooks. The answer is that contractions are graded by recruiting more motor units, under the brain's control. Before you lift something, your brain makes an assumption about the weight of the object and, based on your experience, begins the contraction by stimulating the appropriate number of motor units. If the original number of recruited motor units is incorrect, the brain will adjust by either recruiting more motor units or releasing some extra ones. We have all been fooled at some time. A small bar of silver is far heavier

Myogram • Figure 6.19

During the *latent period*, calcium ions are moving, actin active sites are being exposed, and myosin heads are taking up slack in the myofibers, but contraction is not visible from outside the cell. Once the slack is taken up, the cell suddenly and visibly shortens, causing the sharp rise in the myogram at the *contraction period*. As the calcium is re-sequestered and the actin filaments with associated Z discs are released from the myosin cross bridges, the sarcomeres slide back to their original location. On the myogram, the return to baseline is called the *relaxation period*.



than it looks and can make us feel foolish on our first attempt to lift it. Conversely, lifting a piece of movie-set Styrofoam requires far less force than the brain may rally. On the set of the 1996 disaster flick *Twister*, the semi-trailer that is blown into the air was made of large chunks of Styrofoam. At first, the stagehands threw these Styrofoam chunks into the air after unintentionally using too many motor units to lift them.

Even during tetanus, a small number of muscle cells are relaxing. The pattern of contraction and relaxation is asynchronous. If all the cells functioned in unison, the muscle would bounce between completely contracted to totally relaxed and back to completely contracted! That's a recipe for jittery, stuttering motion.

Muscles Require Energy to Work Smoothly and Powerfully

Now that we have examined the anatomy and physiology of skeletal muscles, it's time to look at how they obtain the energy they need to contract. Let's start by looking at ATP, the general-purpose source of readily available energy inside cells.

aerobic pathway Metabolic pathway that requires oxygen to burn glucose completely.

The body can make ATP for muscular contraction through either the aerobic or anaerobic pathway. The highly efficient **aerobic pathway** burns (oxidizes) glucose, forming water, carbon dioxide, and ATP in the mitochondria. This pathway produces the largest amount of ATP and is the dominant method of energy production.

During heavy muscle activity, the oxygen supply cannot keep up with the energy demands. ATP production then shifts to the **anaerobic pathways**. Anaerobic pathways are less efficient, producing far fewer ATP molecules per glucose molecule. Anaerobic pathways produce lactic acid, which is detrimental to sarcomere functioning. Lactic acid is eventually removed from the tissue by conversion to pyruvic acid, which gets shunted into the **TCA (Krebs) cycle** and the **electron transport chain**. We investigated the TCA cycle and the electron transport system previously. For a quick review, turn back to the discussion on mitochondrial activity in Chapter 4.

anaerobic pathways Metabolic pathways that occur in the cytoplasm and burn glucose to lactic acid, releasing some energy.

TCA (Krebs) cycle The citric acid cycle, step two in the production of ATP from glucose, carried out in the mitochondrial cristae.

electron transport chain Step three in aerobic respiration, wherein electrons are passed along in a series of chemical reactions, eventually producing ATP.

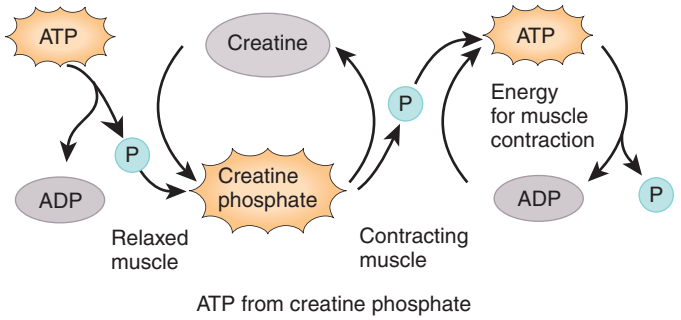
oxygen debt The amount of oxygen needed to convert the lactic acid produced by anaerobic respiration into pyruvic acid and burn it entirely to CO_2, H_2O, and energy.

The conversion of lactic acid to pyruvic acid requires oxygen, which is one reason we breathe heavily after exertion. We are repaying the **oxygen debt** incurred as a result of increased muscular activity. The added oxygen is carried through the bloodstream to the lactic acid-laden tissue. The oxygen reacts with the lactic acid, converting it to pyruvic acid and then to coenzyme A, which the mitochondria can use. All of this activity often produces muscle soreness, as discussed in *What a Scientist Sees: "No Pain, No Gain"* on the next page.

Creatine phosphate is important in the anaerobic phase of muscle energy production because it stores energy much as ATP does, in a phosphate bond. Creatine is a highly reactive compound that picks up the phosphates released when the myosin heads interact with the actin active sites. Recall that the ATP stored in the myosin head is broken into ADP and a free phosphate ion prior to myosin grabbing the actin active site. This free phosphate is released when the myosin head bends toward the center, sliding the actin filament. This freed phosphate ion reacts with creatine to form creatine phosphate. Creatine phosphate then provides a reserve of phosphate for the formation of ATP

Creatine phosphate reaction • Figure 6.20

Creatine picks up free phosphate groups, making them available for the conversion of ADP to ATP, increasing the energy available for muscle contraction.



from ADP. As long as there is a fresh supply of creatine, this cycle will prolong the contracting ability of the tissue. However, eventually even the fittest person will experience muscle fatigue. Figure 6.20 illustrates this cycle.

Muscle Twitches Can Be Fast, Intermediate, or Slow

What causes some muscles to enlarge with exercise, whereas others seem to get stronger without any outward or visible changes? There are three types of muscle cells: **fast twitch** (or fast glycolytic), **intermediate** (or fast oxidative-glycolytic), and **slow twitch** (or slow oxidative). Slow twitch muscle cells appear red, have a large blood supply, have many mitochondria within their sarcolemma, and store an oxygen-carrying protein called **myoglobin**. These cells are sometimes called **nonfatiguing** or **aerobic** cells. Everything about these muscle cells is designed to provide oxygen to the mitochondria to sustain the supply of ATP within the sarcomeres. The large blood supply guarantees continual fresh oxygen flow, and the myoglobin right in the cell captures and holds oxygen for immediate use. Distance running and other aerobic sports stimulate these cells. In these muscle cells, efficiency and strength come not from increasing mass but from using oxygen more efficiently.

WHAT A SCIENTIST SEES

"No Pain, No Gain"

Athletes are often seen massaging sore muscles after a strenuous athletic performance. What causes that soreness? Muscle physiologists are working to unravel the mysteries surrounding muscle soreness. So far, the role of lactic acid has been investigated, as has the ability of the brain to continuously send signals to the muscles. Contracting your muscles at peak performance for long durations can cause physical damage to the muscles and surrounding organs. Perhaps fatigue is a neural checkpoint to prevent this type of damage. Alternatively, fatigue may be a by-product of a buildup of lactic acid in the tissues. Shifting the pH of the muscle cells affects the release and storage of calcium ions. Scientists are interested in observing how athletes deal with muscle pain, as the reduction in pain yields clues to its original cause.

Think Critically

1. Using what you know of the molecular arrangement of sarcomeres and the anatomy of skeletal muscles, can you predict what physical damage might occur with repeated forceful movement?
2. Enzymes and other proteins in muscle cells govern calcium release and storage. What affect does lowering the pH have on proteins such as these? (Hint: Look back at Chapter 3, Section 3.3.)

Fast twitch, or **anaerobic**, muscle cells are almost the total opposite of slow twitch cells. Fast twitch cells provide a short burst of extreme energy and contraction power, but they fatigue quickly. Fast twitch cells are thicker, contain fewer mitochondria, usually contain larger **glycogen** reserves, and have a less developed blood supply. These are the cells that are responsible for hypertrophy. Because short bursts of power come from these fibers, exercises that continuously require bursts of power will enlarge them. Weight training puts demands on fast twitch fibers, resulting in the hypertrophy (muscle enlargement) we associate with bodybuilding.

glycogen A large polysaccharide easily broken down to release individual glucose molecules.

Although physical training can alter the functioning of both red (slow twitch) and white (fast twitch) fibers, it does not change their proportions. Your percentage of fast and slow twitch fibers is genetically determined. However, training can cause fast twitch fibers to function more like slow twitch fibers, providing more endurance with increased exercise. The ratio can, however, differ for each muscle group. You may have a preponderance of fast twitch fibers in your shoulder and back muscles, whereas your quadriceps muscle group may contain more slow twitch fibers. Olympic-caliber athletes are often those blessed with higher percentages of red or white fibers than the average person. Sprinters, obviously, benefit from a high proportion of fast twitch muscles, while long-distance skiers need more aerobic muscle cells.

Toned Muscles Work Better, Look Better

When muscles are used often, we say they have "good **muscle tone**." What we are really saying is that even at rest, some muscle cells are always contracted. In a toned muscle, individual cells sporadically contract and relax, causing no movement but keeping the muscle taut. We can see muscle definition through the skin, due to this partial contraction. Increased tone is an important benefit of regular exercise, and not just for the "buff" look. Toned muscles are more effective at burning energy, meaning they use more ATP per gram than less-toned muscle tissue. People who are in shape can eat more without gaining weight because that continual, low-level contraction burns ATP. The bottom line is that a well-exercised body burns more calories in a day than an inactive body.

muscle tone Constant partial contraction of muscle when the body is "in shape."

Exercise or chemical compounds can also change the size of a muscle. For those who want a shortcut to big, powerful muscles, testosterone and related steroid hormones have long been drugs of choice. Steroid hormones are based on cholesterol, and their lipid structure gives them the ability to diffuse through the plasma membrane. Steroid hormones that cause muscle growth are called anabolic steroids. Once inside the muscle cell, anabolic steroids stimulate the production of proteins, such as actin, myosin, and dystrophin, which bulk up existing muscle cells.

The side effects of anabolic steroids, which can include liver dysfunction, testicular disease, and kidney disease, are so severe that anabolic steroids are regulated by the same laws that cover morphine. They are also banned by a growing list of professional sports organizations.

The skeleto-muscular system can be enhanced when injury or problems from birth result in deviations to the system that produce stronger muscles and bones. Also, the muscular system is the organ system that can be altered most greatly by lifestyle choices. Scientists think the total number of muscle fibers is essentially set at birth, so how do we alter the appearance of this system? We can do it through muscle enlargement or **hypertrophy** (*hyper* = above; *trophy* = to grow). Scientists believe hypertrophy is caused by the addition of new myofibrils within the endomysium of individual muscle cells, which thickens individual myofibers. Thus, hypertrophic muscles should have thicker muscle cells, packed with more sarcomeres than nonhypertrophic muscle cells. Exercise that requires muscle to contract to at least 75% of maximum tension will cause hypertrophy. Bodybuilders use this knowledge to create their sculpted figures. Interestingly, aerobic exercises like cycling and dancing will not cause hypertrophy, but they still provide the cardiovascular and metabolic effects of increased muscle tone. Some people believe muscles can be built without any exercise at all. To read more on this, go to *I Wonder… Can I Really "Think" My Way to Better Athletic Performance?* on the next page.

I WONDER...

Can I Really "Think" My Way To a Better Athletic Performance?

Sports psychologists indicate that you can improve your athletic performance through mental imagery. Mental imagery is not easy. Sitting quietly in an empty room and visualizing the performance of a skill or the running of a race, moment by moment, is a challenge in focus. The athlete must create the scenario explicitly in the mind. The athlete should focus not only on the muscular movements involved in the activity, but also on the sounds, smells, sights, and even moods that are experienced while performing the activity. Nothing should be omitted, so that the brain creates as close to an actual event as possible. If the event is a swimming event, even the taste of the water should be visualized.

Does this technique work? Researchers are divided in their findings. In some cases, performance did increase, and skills were perfected. In others, there was no appreciable gain, and even some loss in performance. Analysis of the published data is difficult to interpret due to the lack of good controls in some cases and the anecdotal quality of other reports. Physiologists do agree that strong visualization techniques excite neuromuscular patterns in the brain exactly as they are triggered by the performance. In other words, good visualization creates pathways in the brain that may be used during athletic performance. When you visualize, it is as if you are throwing that basketball over and over, without fatigue. If you are serious about your performance, mental imagery is worth a try!

CONCEPT CHECK

1. **What** is meant by the all-or-nothing basis of muscle contraction?
2. **How** are summation and tetanus related to one another?
3. **What** is the difference between the aerobic and anaerobic energy pathway?
4. **What** are the characteristics of the three different types of muscle fibers?

Summary

THE PLANNER

1 The Skeleto-Muscular System Is Multifunctional and Dynamic 120

- The functions of the skeleto-muscular system include providing movement and locomotion, manipulating our environment, protecting the organs in our thoracic and abdominopelvic cavities, maintaining homeostasis by generating internal heat, maintaining our upright posture and our bipedal way of life, carrying out hematopoiesis, and storing and releasing minerals.
- Despite our changing responsibilities for our own survival, the interaction of the skeletal and muscular systems remains vital.
- Bones support muscle, and muscles provide movement to the bones and joints.

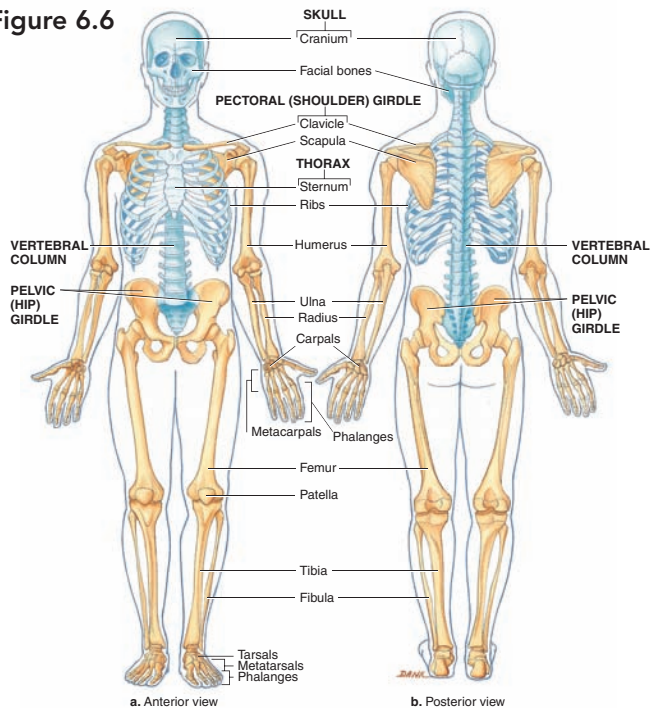
2 Bone Is Strong and Light Tissue 122

- Bone is connective tissue produced by osteoblasts. They are formed by either endochondral or intramembranous ossification.
- Bone is either compact or spongy. Compact bone is composed of osteons in regular arrangements. Bones are surrounded by a periosteum, which is continuous with the outer covering of skeletal muscles. The anatomy of a long bone includes articulating cartilage, diaphysis, epiphysis, and a medullary canal filled with marrow.
- Osteoclasts destroy bone, whereas osteoblasts make new bone. These processes are in response to changing blood calcium levels. Healing broken bones is similar to creating new bone, using the same cells.

3 The Skeleton Holds It All Together 127

- The skeleton is composed of 206 bones, classified as long, short, flat, irregular, sesamoid, or wormian.
- As shown, the axial skeleton includes the skull, vertebrae, sternum, and ribs. The skull has 14 facial bones and 8 cranial bones. The appendicular skeleton consists of the pectoral girdle, the arms and hands, the pelvic girdle, and the legs and feet. There are anatomical differences between male and female pelvic girdles.

Figure 6.6

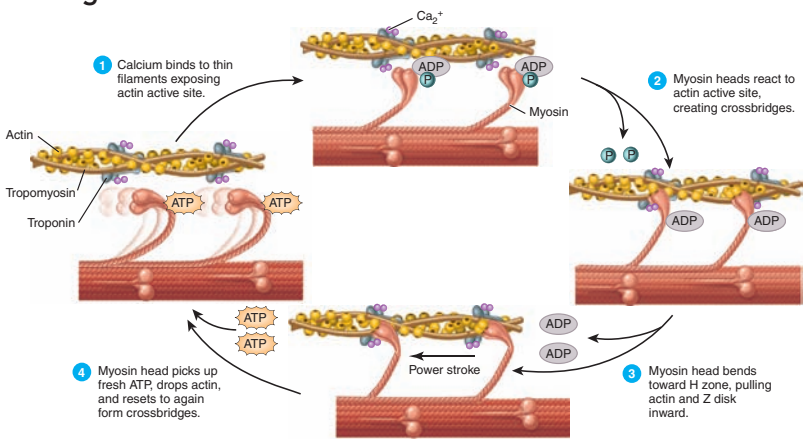


- Joints are classified either by structure or function, with synovial joints being the most common. Many movements are permitted at synovial joints.

4 Skeletal Muscles Exercise Power 137

- Skeletal muscles are highly organized, with an epimysium, perimysium, and endomysium covering the organ and its cells. The cells within these layers are called myofibers.
- As you can see here, actin and myosin are the proteins responsible for the contraction of skeletal muscle.

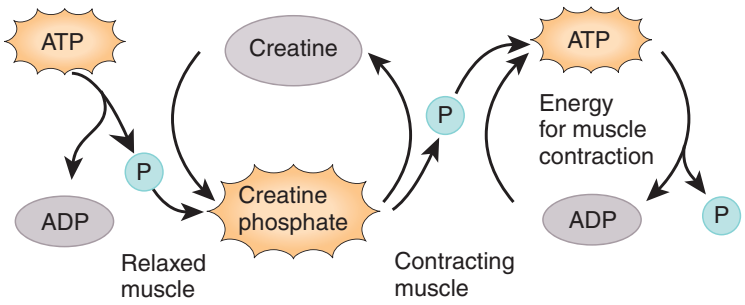
Figure 6.17



- The contractile proteins are arranged in sarcomeres, with light and dark bands visible under a light microscope.
- Contraction of skeletal muscle begins at the synapse between a motor neuron and a myofiber. The neuromuscular junction has specialized structures that help propagate the contraction.
- Muscle contraction is referred to as the sliding filament theory and involves actin fibers sliding past myosin fibers. This process takes ATP, and muscles cannot relax without a fresh supply of ATP.

5 Whole-Muscle Contractions Require Energy 144

- Muscle contraction is an all-or-nothing activity and involves motor units.
- Muscles contract as single twitches that last only a fraction of a second. Tetanus is a continuous state of contraction brought about by repeated stimulation of motor units.
- Muscle contraction requires energy. ATP is the usual form of energy, produced aerobically. This illustration demonstrates that creatine phosphate serves as a reserve energy source, allowing sustained movement for short periods of time. Anaerobic respiration can produce some energy, but also builds up lactic acid in the muscles.



ATP from creatine phosphate

Figure 6.20

- Muscle fibers are either fast glycolytic cells, intermediate fast oxidative glycolytic cells, or slow oxidative cells. The difference lies in the energy they carry within them and the number of mitochondria and capillaries nourishing the cells.

Key Terms

- aerobic pathway 145
- anaerobic pathways 145
- antagonistic (synergistic) pair 138
- articulates 129
- bursa 136
- cribriform plate 129
- electron transport chain 145
- fossa 130
- glycogen 147
- graded contraction 144
- menisci 136
- muscle tone 147
- myofibrils 140
- osteoblasts 122
- osteocytes 122
- oxygen debt 145
- parietal 129
- pectoral girdle 132
- pelvic girdle 130
- skeletal muscle 137
- synovial fluid 136
- T tubules 140
- TCA (Krebs) cycle 145
- threshold stimulus 144

Critical and Creative Thinking Questions

1. When hiking in the backwoods, you come across a human skeleton. What clues can you use to determine the identity of the deceased? How would you determine gender? Can you determine age, dietary preferences, general health, and occupation? What markings or other signs would you consider valuable clues?
2. CLINICAL CLICK QUESTION

   Randy is a typical boy of 11. He enjoys riding his bike, skateboarding, and running endlessly. Last year, Randy discovered a talent for cross country running when he won his area's All-County Middle School cross country competition. This year however, he has found that he is not as fast. Randy complains of excessive tiredness, and often will drop out of simple training runs. Additionally, he has found that he loses his balance when walking, and is occasionally embarrassed by a lack of coordination. Is Randy's problem one that is affecting muscles, bones, or the nerves that govern muscle movements?

   His doctor began charting Randy's leg muscle mass, and within a year noticed that the muscle mass in his once-powerful leg muscles is diminishing. After 12 months, Randy was no longer able to hop or jump without falling.

Using these symptoms as key words in an Internet search engine, see if you can diagnose Randy's illness. For help with this, go to http://www.nlm.nih.gov/medlineplus/ency/article/000706.htm

Unfortunately, his problem is an inherited genetic defect. Why is there no cure for this? The muscle wasting will slowly continue over decades, eventually affecting skeletal muscle groups other than those of his legs. How can this disease cause death?

3. In Greek mythology, Achilles was a heroic warrior, undefeated in many battles. His undoing was an arrow to the tendon of the gastrocnemius muscle (see Figure 6.14 for the exact position). Using the terms *origin*, *insertion*, and *belly*, explain the location of his wound. In common language, why did the arrow end Achilles' fighting career? Anatomically speaking, what destroyed his fighting ability?

4. List the sources of energy that are readily available for muscle contraction. What happens in endurance events? Where do the muscles of the leg get their steady energy supply during a grueling athletic event like a marathon? Does it make sense for endurance athletes to take in nutrients during events?

5. We know that training affects muscle fibers by making them more efficient. Specifically how does this occur? Assume that you have begun endurance training for the Tour de France. What will this training do for your red muscle fibers? For your white and intermediate muscle fibers? Can training alter the proportion of these fibers?

What is happening in this picture?

This woman is running a sprint leg of a four-person relay in a typical college track meet. She has taken the baton and is expected to run as fast as she can for 400 yards. Most of the people in the stands see her running and think of the physical difficulties she is enduring. Scientists, however, see a bit more. Can you observe more from her race?

Think Critically

1. You see that she is breathing regularly. What does that suggest about her energy usage? Will the race last long enough for her to tap all her ATP reserves? How will she replace those reserves?
2. You notice that she breathes heavily for only a minute or two after her effort. What does that tell you about her fitness level?
3. Finally, you observe that she was able to pop off the line quickly with the baton, gaining ground immediately on her competitors. What does that tell you about the muscle fibers of her hamstrings, quadriceps, and gastrocnemius?

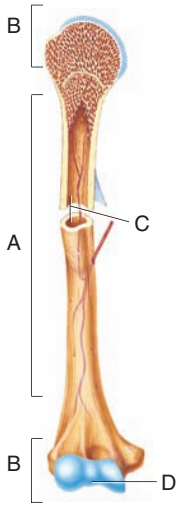
NATIONAL GEOGRAPHIC

Self-Test

1. The axial skeleton includes _____.
   a. the carpals
   b. the phalanges
   c. the ribs
   d. the clavicle

2. Which of the bone types is formed inside tendons?
   a. long bones
   b. sesamoid bones
   c. short bones
   d. wormian bones

3. Identify the portion of a long bone indicated as B in this figure.
   a. diaphysis
   b. epiphysis
   c. medullary canal
   d. articulating cartilage

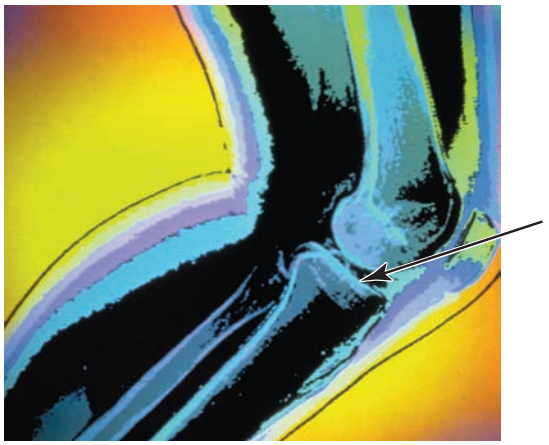


4. During bone remodeling, the cell responsible for breaking down bone and releasing the stored calcium is the _____.
   a. osteoblast
   b. osteoclast
   c. osteocyte
   d. osteo

5. _____ hipbones are thicker, narrower, and have a narrow pubic angle.
   a. Male
   b. Female
   c. Infant
   d. Adult

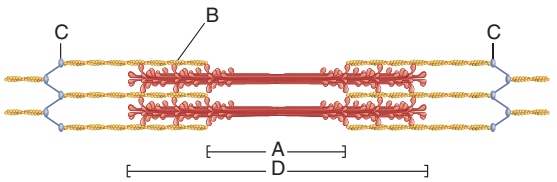
6. The type of joint typically found in the skull is a _____.
   a. synarthrotic joint
   b. synovial joint
   c. amphiarthrotic joint
   d. diarthrotic joint

7. The structure identified in this diagram of a synovial joint is the _____.
   a. synovial fluid
   b. bursa
   c. meniscus
   d. articular cartilage

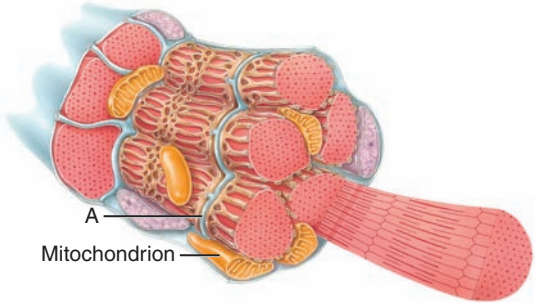


8. Looking at your own biceps brachii (the muscle that allows you to flex your arm), locate its insertion.
   a. the humerus
   b. the elbow
   c. the radius
   d. the carpals

9. The label that indicates the actin filaments on this diagram of a sarcomere is _____.
   a. A
   b. B
   c. C
   d. D



10. The structure indicated as A in this figure serves to _____.
    a. sequester calcium
    b. house actin and myosin
    c. protect the muscle cell
    d. carry the impulse to contract quickly through the entire cell

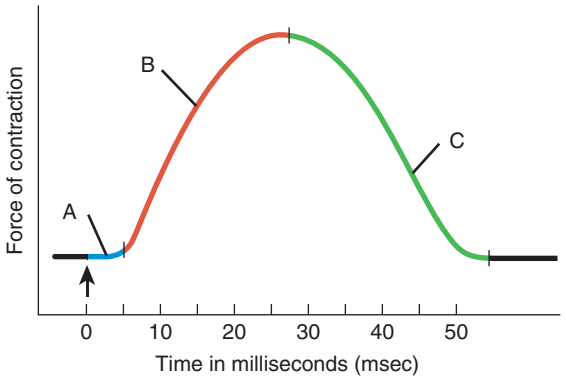


11. The contractile unit of skeletal muscle is the _____.

a. sarcomere
b. sarcolemma
c. epimysium
d. osteon

12. The portion of the myogram indicated as B corresponds to what action?

a. relaxation
b. a latent period
c. contraction
d. calcium sequestering

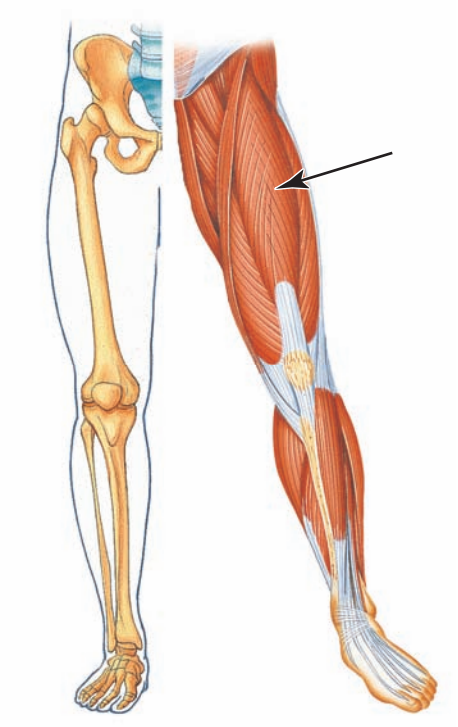


13. The most efficient production of energy for muscular contraction is _____.

a. aerobic pathways
b. anaerobic pathways
c. lactic acid metabolism
d. creatine phosphate

14. The muscle indicated on the figure is the _____.

a. biceps brachii
b. rectus femoris
c. rectus abdominus
d. pectoralis major



15. The insertion for the muscle shown in question 14 is on the _____.

a. femur
b. humerus
c. tibia
d. pelvic bone

THE PLANNER

Review your Chapter Planner on the chapter opener and check off your completed work.

7 The Nervous System

The brain is arguably the most complex organ in the human body. As scientists continue to investigate brain functioning and neural patterns, new and often surprising discoveries are made. Most recently, the powerful effects of music on the human brain have been documented. It has been known for some time that listening to music stimulates the brain. Dr. J.S. Jenkins, of London's Royal Society of Medicine, has written extensively on the apparent link between music perception and spatial imaging. Most interestingly, he notes that researchers have documented many different areas of the brain activated by music appreciation. Using scanning techniques such as positron emission tomography (PET) and functional magnetic resonance imaging (fMRI), it is now commonly accepted that music is interpreted not only in the expected primary auditory area, but also in the prefrontal area and deeper sections of the brain normally active during spatial and temporal tasks. Listening to music is a "whole brain" activity, meaning that both the left and right hemispheres are activated by music. The left hemisphere is stimulated by rhythm and pitch, while the right hemisphere responds chiefly to melody and timbre. When a popular tune or advertising jingle gets "stuck in your head," it is apparently the right hemisphere that is triggering that annoying re-playing. Dr. Oliver Sacks, a neurologist and successful author, has recently published a book of patient case studies documenting the often-amazing effects music has had on their brain functioning. Dr. Sacks has seen music calm the perpetually confused, help to motivate the catatonic, and restore the power of speech to stroke victims while the tune is playing.

WILEY PLUS Video

NATIONAL GEOGRAPHIC

CHAPTER OUTLINE

The Nervous System Is Categorized by Structure and Function 156

- The Nervous System Has Two Components
- Nervous Tissue Is Made of Neurons and Glial Cells

Neurons Work Through Action Potentials 160

- Gates and Channels Control the Flow of Ions
- Action Potentials Work at Different Speeds
- Synapses Separate One Neuron from Another, and Neurotransmitters Bridge the Gap
- Graded Responses Create Fine Neural Control

The Brain and Spinal Cord Are Central to the Nervous System 167

- The Meninges and Cerebrospinal Fluid Protect and Nourish the Central Nervous System
- The Brain Has Four Main Parts
- The Cerebrum Is a Central Processing Center
- The Reticular Activating System Is the Brain's Alarm Clock
- The Spinal Cord Connects to Almost Everywhere

The Peripheral Nervous System Extends the Central Nervous System 180

- The PNS Also Contains Sympathetic and Parasympathetic Nerves

CHAPTER PLANNER

- ❑ Study the picture and read the opening story.
- ❑ Scan the Learning Objectives in each section:
  p. 156 ❑ p. 160 ❑ p. 167 ❑ p. 180 ❑
- ❑ Read the text and study all figures and visuals. Answer any questions.

Analyze key features

- ❑ Process Diagram, p. 162
- ❑ What a Scientist Sees, p. 165
- ❑ Health, Wellness, and Disease, p. 166
- ❑ Biological InSight, p. 171
- ❑ Ethics and Issues, p. 172
- ❑ I Wonder..., p. 174
- ❑ Stop: Answer the Concept Checks before you go on:
  p. 160 ❑ p. 167 ❑ p. 179 ❑ p. 181 ❑

End of chapter

- ❑ Review the Summary and Key Terms.
- ❑ Answer the Critical and Creative Thinking Questions.
- ❑ Answer What is happening in this picture?
- ❑ Answer the Self-Test Questions.

7.1 The Nervous System Is Categorized by Structure and Function

LEARNING OBJECTIVES

1. **List** the functions of the nervous system and the three types of receptors in the afferent nervous system.
2. **Explain** the differences between the somatic and autonomic divisions of the efferent peripheral nervous system.
3. **Describe** the structure of neurons and give the function of the associated neuroglia.

Lift this book. Turn the page. Scan the words with your eyes and understand them with your brain. All of these actions are directed by the nervous system. Brush a bothersome hair off your face. Listen to tires crunch the pavement as a car drives past. Smell the flowers outside. All of these sensations are brought to you compliments of the nervous system. Every conscious action that occurs in your body is governed by the nervous system, as are most of the "unconscious" or automatic actions that maintain homeostasis.

When skeletal muscles contract, they do so in response to stimuli from the nervous system. We plan our movement in the brain, and the nervous system transmits that plan to the muscles. At the muscles, the nervous system stimulates only those motor units needed for that particular task. In Chapter 6 you learned about neuromuscular junctions.

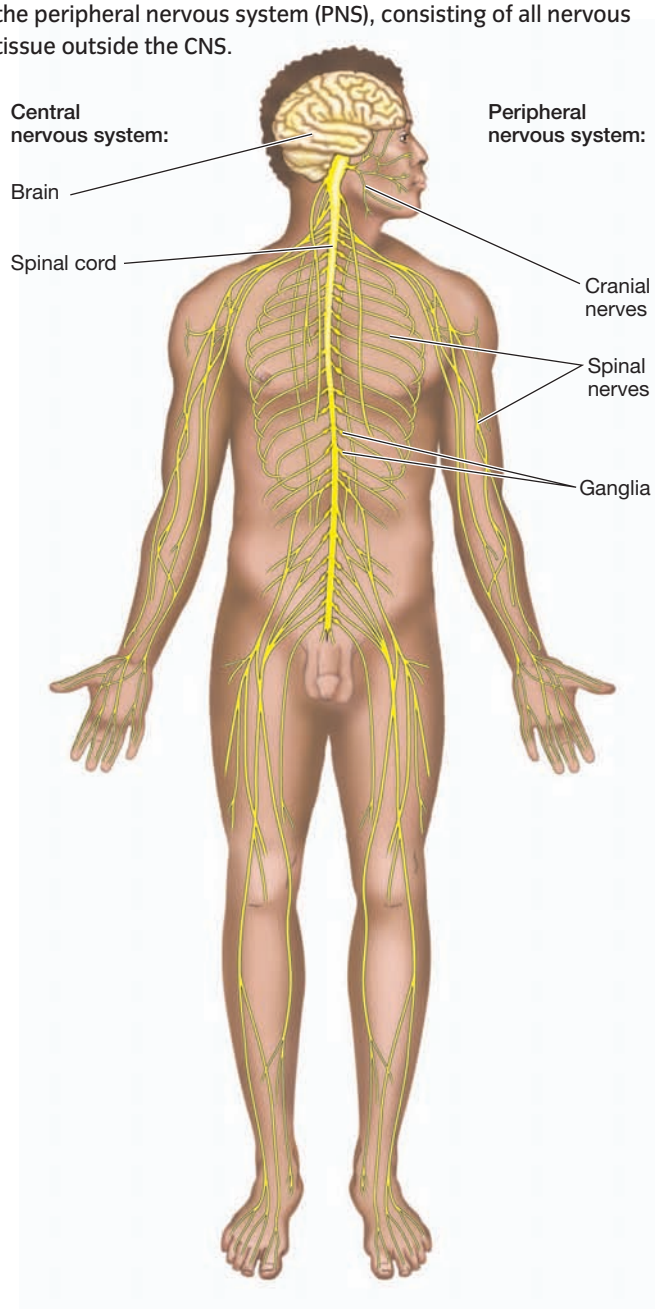
Although this type of activity is familiar, the nervous system has many other functions, some better understood than others. The nervous system is used to communicate from one end of the body to another. The nervous system receives and integrates stimuli and formulates an appropriate response. The stimulus can be an external change, such as a shift in temperature or sound, or it can be an internal change, such as a localized decrease in blood pressure or a general increase in carbon dioxide levels in the tissues. Whatever the change, the nervous system's job is to immediately detect it and adapt in order to maintain homeostasis. It is this immediacy that sets the nervous system apart from other control systems of the body.

The Nervous System Has Two Components

The nervous system has two components: the **central nervous system** (CNS) and the **peripheral nervous system** (PNS), as shown in Figure 7.1. The distinction is based mainly on location. The CNS includes the **brain** and **spinal**

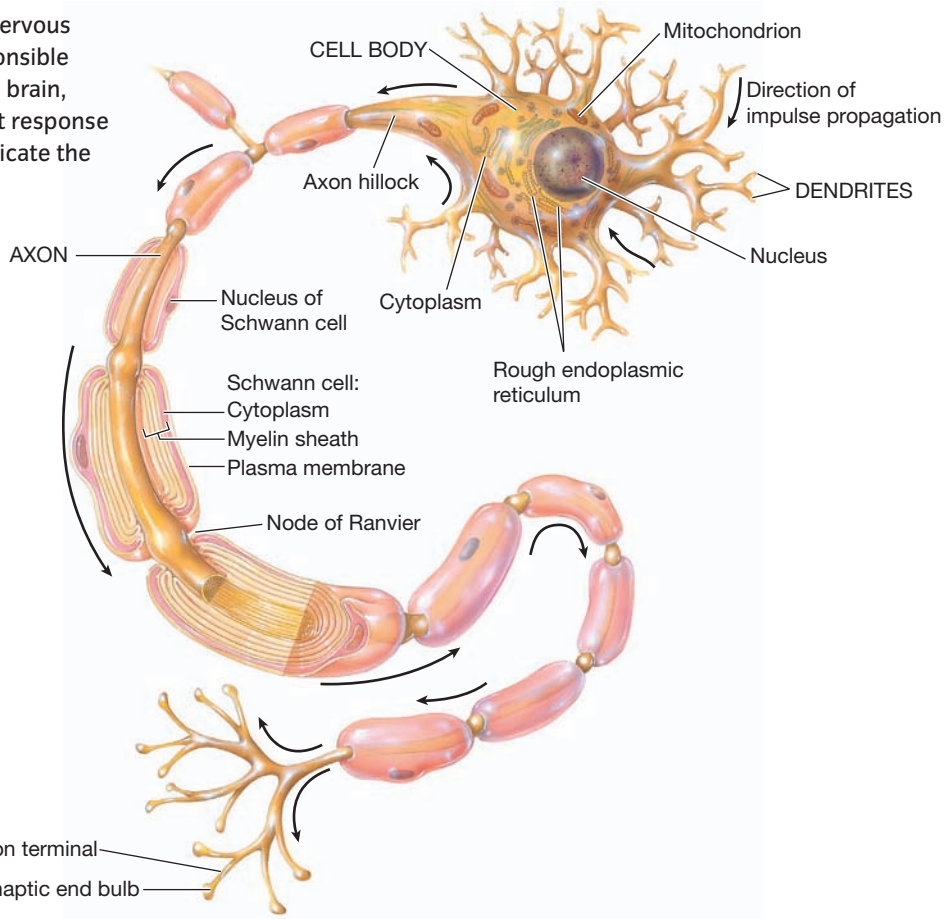
Divisions of the nervous system • Figure 7.1

The two main divisions of the nervous system are the central nervous system (CNS), consisting of the brain and spinal cord, and the peripheral nervous system (PNS), consisting of all nervous tissue outside the CNS.



Neuron • Figure 7.2

The neuron is the functional unit of the nervous system. These remarkable cells are responsible for carrying sensory information into the brain, formulating a response, and sending that response out to the proper organs. The arrows indicate the direction of impulse propagation.



cord. It lies encased in the axial skeleton and is covered by the meninges. The CNS is the main integration center of the body. Sensory information comes in to the CNS, where it is analyzed and an appropriate motor response is generated. The motor response is usually directed toward muscular or glandular tissue.

afferent Toward an organ; in this case, neurons that carry information towards the CNS.

efferent Away from an organ; in the nervous system, neurons that carry information away from the CNS.

neuron A nerve cell that sends and receives electrical signals.

neurotransmitter A chemical used to transmit a nervous impulse from one cell to the next.

The PNS extends the CNS.

The PNS is composed of all the **afferent** and **efferent** neurons that extend from the CNS. In both the PNS and CNS, nervous information is carried by **neurons** and passed from one cell to the next using **neurotransmitters**. See **Figure 7.2** for details on the neuron's structure and function. The neurons of the PNS are arranged in bundles called **nerves**. Nerves can be motor, sensory, or mixed, depending on what type of neurons they contain.

Most information going to and from the central nervous system travels through the peripheral nervous system. Information reaches the CNS from the afferent division of the peripheral nervous system. The PNS picks up this information with one of three types of receptors: special senses, general sensory receptors, or visceral receptors. These receptors allow us to experience many different sensations. Our **special senses** enable us to see, hear, taste, and smell the external world. Our skin has **general sensory receptors** that inform us about external temperature as well as light touch, pressure, and pain. Within our bodies, visceral receptors monitor **proprioception** and organ functioning. Stomach aches and sore throats are examples of visceral sensory input.

proprioception The reception of stimuli from within the body that give information on body position and posture.

Motor responses are formulated in the CNS and taken to the muscles or glands by the efferent division of the PNS. Again, the impulses can travel on different pathways. To

consciously move skeletal muscle, we plan an activity in the CNS and then direct the muscles to carry it out through motor commands sent by the **somatic division** of the PNS. This division is sometimes called the voluntary division, because the motor commands are consciously, and therefore voluntarily, controlled. However, the involuntary movement of reflexes is also part of this division. The same motor neurons that stimulate reflexive movements are used for conscious movements.

somatic division Division of the nervous system involved in conscious movement.

The autonomic nervous system has two parts and works even while you sleep. The **autonomic division** of the PNS, also known as the ANS, is a control system that governs your body's responses to subtle changes in homeostasis with involuntary, unconscious reactions. For example, the CNS continually generates responses to sensory input concerning blood pressure, blood gases, and visceral functioning. You are not aware of these inputs, nor do you control the motor responses that travel through the autonomic nervous system.

autonomic division (ANS) Division of the nervous system regulating functions such as blood vessel diameter and stomach activity.

The autonomic nervous system has two subdivisions (Table 7.1). The first subdivision, the **sympathetic division**, includes those nerves that control the body when it is actively moving and burning energy. The sympathetic division is sometimes called the "fight or flight" division, because it is triggered when we feel threatened and must choose to remove ourselves from the danger (flight) or stay and "fight." The **parasympathetic** division is responsible for digestion, energy storage, and relaxation. These divisions are nicely separated by the contradictory demands of human life: sometimes we must conserve energy and rest; other times we must move quickly and expend energy.

Almost every organ of your body has dual innervation, meaning that it is stimulated and controlled by both the sympathetic and the parasympathetic divisions. The two systems work antagonistically to maintain homeostasis. If the organ is burning energy, releasing oxygen or glucose into the bloodstream, or otherwise aiding in sharp mental capacity and quick responses, the sympathetic division is working. If the organ's function is conducive to rest and relaxation, you can bet the parasympathetic division is in control.

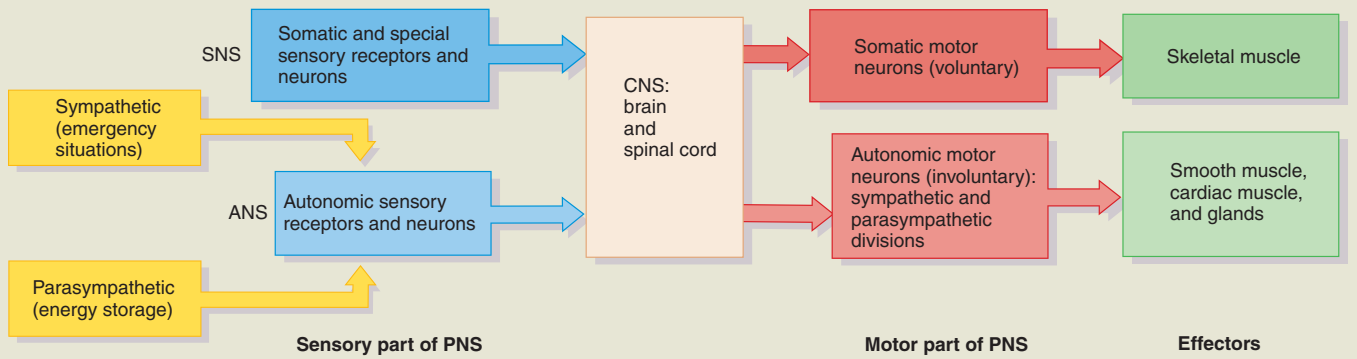
The functions of these two divisions are easy to remember. The sympathetic division is sympathetic to your plight. It is active when you need quick energy and rapid movement. The parasympathetic division starts with "P," like potato. When this system is active you are relaxing—acting like a "couch potato."

Nervous Tissue Is Made of Neurons and Glial Cells

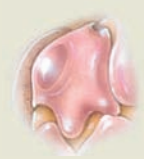
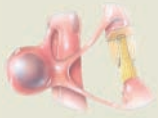
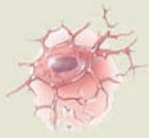
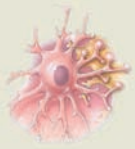
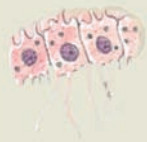
Nervous tissue, one of the four main tissue types, is composed of neurons and supporting cells called **neuroglia** or simply glia (singular: *neuroglion*). The types and functions of the neuroglia are listed in Table 7.2. The three

neuroglia Cells that support and protect within the nervous system, including cells that provide nutrients, remove debris, and speed impulse transmission.

Outline of the nervous system, comparing the sympathetic and parasympathetic characteristics Table 7.1



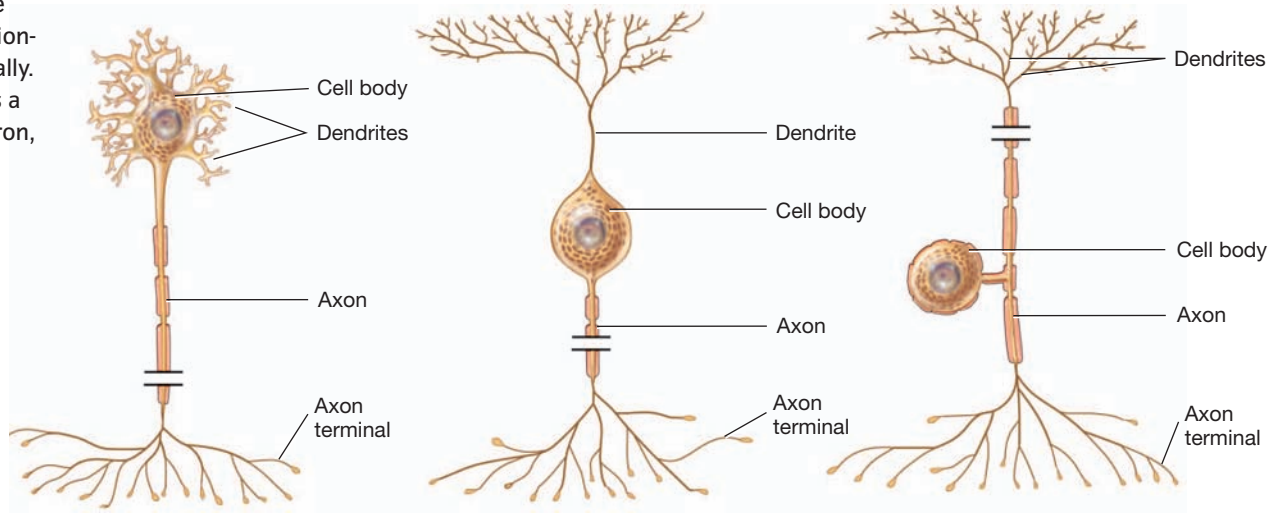
Neuroglia size and shape, location, and function Table 7.2

Name	Function	Name	Function
PNS			
Satellite cells 	Regulate oxygen, carbon dioxide, nutrient, and neurotransmitter levels around ganglia	**Schwann cells** 	Surround axons in PNS, causing myelination of axons and faster impulse transmission, aid in repair after injury
CNS			
Oligodendrocytes 	Surround CNS neuron processes, provide structural support	**Microglia** 	Clean up cellular debris and pathogens via phagocytosis
Astrocytes 	Maintain blood-brain barrier; regulate nutrient, ion, and dissolved gas concentrations; absorb and recycle neurotransmitters; form scar tissue after injury	**Ependymal cells** 	Line ventricles and central canal of spinal cord, assist in cerebrospinal fluid production

classes of neurons are based on function: **motor neurons, interneurons**, and **sensory neurons**, as shown in Figure 7.3. Each type has a distinctive shape, which allows ready identification. Despite their anatomical differences, all neurons have a cell body, one axon, and at least one dendrite. The dendrite(s) bring information

Motor neurons, interneurons, and sensory neurons • Figure 7.3

Neurons can be classified functionally or structurally. Structurally a is a multipolar neuron, b is a bipolar neuron, and c is a unipolar neuron.



a. Motor neuron **b. Interneuron** **c. Sensory neuron**

to the cell body. There can be many dendrites, with the branches providing many avenues for incoming impulses. The single axon routes the nerve impulse from the cell body to another neuron or an effector organ. The axon can have many terminal branches, so each time the nerve fires, it can stimulate more than one cell.

CONCEPT CHECK STOP

1. **What** are the main functions of the nervous system?
2. **What** are the three types of receptors in the afferent nervous system?
3. **What** are the differences between the somatic and autonomic divisions of the efferent peripheral nervous system?

7.2 Neurons Work Through Action Potentials

LEARNING OBJECTIVES

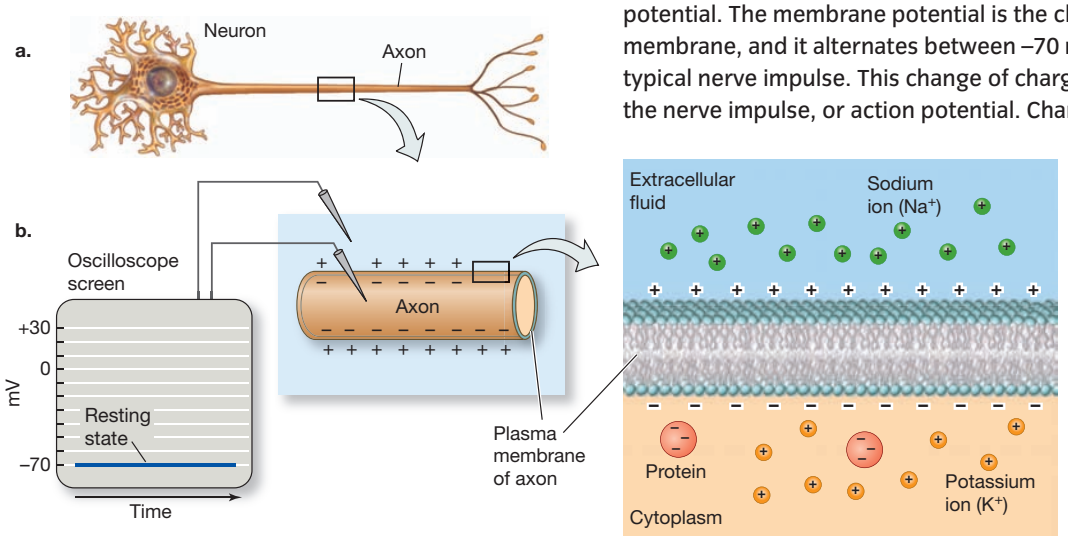
1. **Differentiate** action potential from membrane potential.
2. **Describe** the types of channels found in neuron membranes.
3. **List** the events in an action potential.
4. **Describe** the events at a typical synapse.

An action potential is a brief change in electrical conditions at a neuron's membrane that occurs when a neural signal arrives; it is what happens when we say a neuron "fires." At the molecular level, what allows neurons to carry electrical impulses? How do these oddly shaped cells receive, integrate, and respond to information? The answers begin with the electrical conditions surrounding the neuronal membrane. These electrical conditions create a **membrane potential** across the neurolemma that is exploited when the nerve fires, as shown in Figure 7.4.

membrane potential The difference in electrical charge between two sides of a membrane.

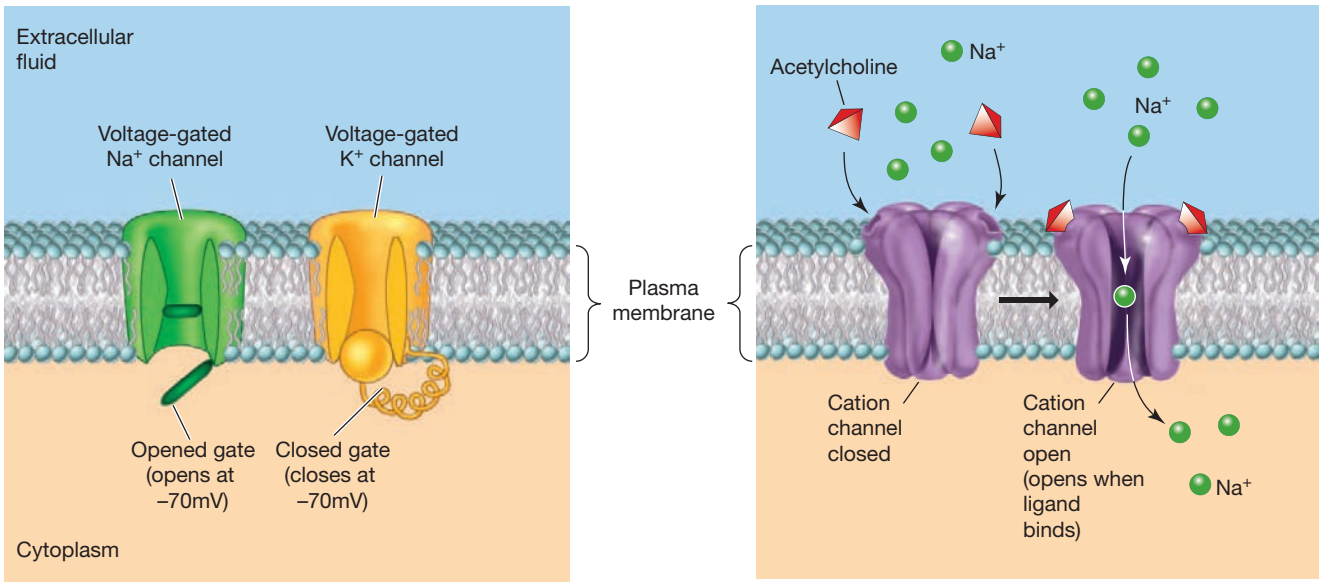
A resting neuron has a membrane potential of –70 mV. This charge is measured using a voltmeter. The difference in charge between the inside

Membrane potential • Figure 7.4



Unlike most body cells, neurons can significantly alter their membrane potential. The membrane potential is the charge difference across the membrane, and it alternates between –70 mV and +30 mV during a typical nerve impulse. This change of charge across the membrane is called the nerve impulse, or action potential. Charge differences are controlled by the movement of sodium and potassium ions entering and leaving the neuron. A resting neuron (not firing) has a membrane potential of –70 mV, as shown in the oscilloscope.

Gated channels • Figure 7.5



a. Voltage-gated channels

b. Ligand-gated Na^+ channel

and outside environment of the nerve cell membrane is read by the voltmeter and displayed on an oscilloscope (Figure 7.4). During the normal resting condition, the levels of positive sodium ions and negative chloride ions are higher outside the neuron than inside. Conversely, positive potassium ions are more concentrated inside the neuron than outside. Large, negatively charged proteins trapped in the neuron help to maintain the negative charge across the membrane. In the absence of a selectively permeable membrane, the differences would rapidly disappear as the ions diffused down their respective concentration gradients. Sodium would diffuse into the cell, potassium would diffuse out, and the negative charges would balance.

This diffusion does not happen, however, because ions cannot simply diffuse through the lipid bilayer of the cell membrane. Instead, they must travel through channel proteins that serve as portals for ion diffusion. Channel proteins can be either passive or active. Passive channels are "leaky" and allow a constant trickle of ions. Active channel proteins allow no ion movement unless stimulated. This means the rate of ion movement across the nerve cell membrane depends on the physical state of the channel proteins, which can vary greatly from moment to moment. The variation in ion concentration across the cell membrane allows neurons to generate action potentials.

Gates and Channels Control the Flow of Ions

Active channels are often called **gated** channels, because they allow ion transport only under specific environmental conditions. A gated channel is one of the following:

- **Voltage gated**, opening and closing in response to transmembrane voltage changes, as shown in Figure 7.5a
- **Ligand gated** (chemically regulated), opening and closing when the proper chemical binds to them, as shown in Figure 7.5b
- **Mechanically regulated**, responding to physical distortions of the membrane surface (not shown)

At rest, gated channels are closed. When open, these gates allow ions to cross the membrane in response to their concentration gradients, changing the transmembrane potential and generating a nerve impulse. Figure 7.6 on the next page, outlines the steps of an action potential.

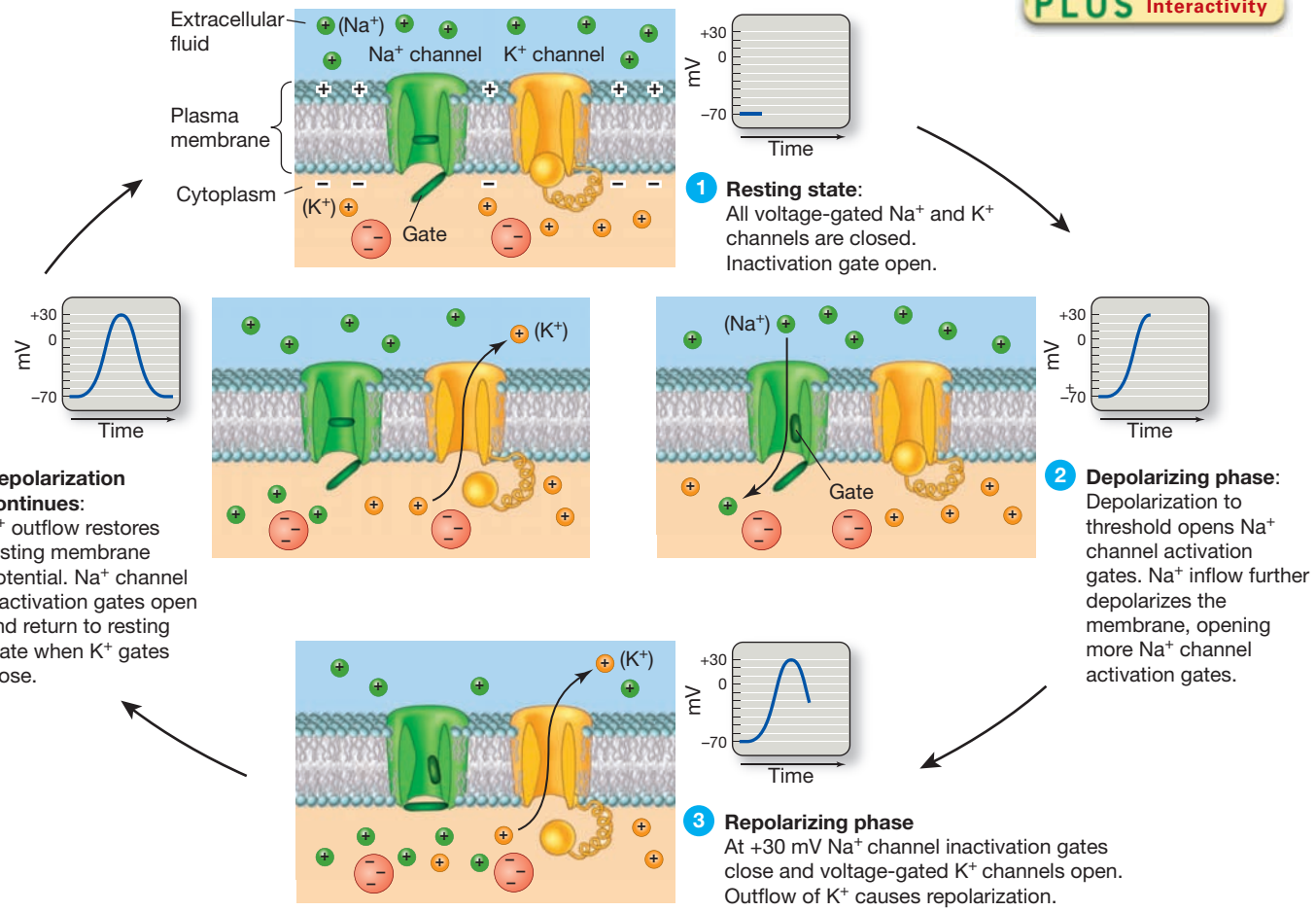
From the moment the sodium channels open until they reclose, the neuron cannot respond to another action potential. There are two phases to this inactive period. During the **absolute refractory** period, which lasts from 0.4 to 1.0 milliseconds, sodium and potassium channels are returning to their original states. Because the sodium channels are inactivated during the absolute refractory period, it is impossible to generate a second action potential. The **relative refractory period** begins when the

PROCESS DIAGRAM

Neuron action potential • Figure 7.6

THE PLANNER

WILEY PLUS Interactivity



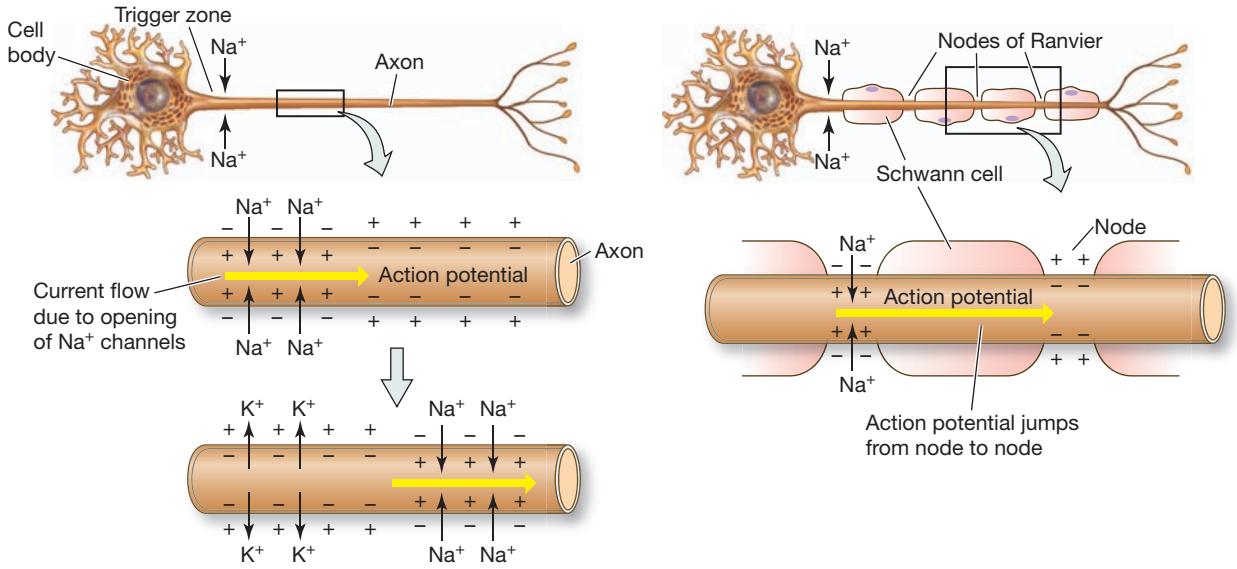
sodium channels are again in resting condition, and it continues until the transmembrane potential stabilizes at –70 mV. The **sodium potassium exchange** pump (Na^+/K^+ ATPase) helps stabilize the cell at the initial ion concentrations by moving three sodium ions out of the cell and two potassium ions into it.

Scientists used to believe that Na^+/K^+ ATPase was needed for the neuron to carry another action potential, but now it seems that it need not operate after every nerve impulse. Enormous numbers of sodium and potassium ions are on either side of the membrane, and the subtle concentration changes of one action potential do not block impulse transmission. It would take literally thousands of consecutive action potentials to alter the ion concentrations enough to destroy the overall mechanism. The Na^+/K^+ ATPase merely helps return the local membrane potentials quickly so a second action potential can be generated.

Action Potentials Work at Different Speeds

Nerves can propagate action potentials at different speeds. Nerve impulses are sent along the axon in wavelike fashion. Impulses always begin at the swollen base of the axon—the axon hillock. These impulses travel along the membrane to the axon terminus, where they stimulate the release of neurotransmitters. Propagation speed

Impulse conduction • Figure 7.7



can be influenced by the diameter of the axon (thick axons propagate faster) and by the amount of **myelin** on the axon (Figure 7.7). When the axon is wrapped in a myelin sheath, action potentials travel in a jumping pattern. The actual movement of sodium and potassium ions occurs only at the nodes, those stretches of naked axon visible between the cells that create the myelin sheath. Voltage-gated channels are concentrated at these nodes. The action potential can travel much faster along the nodes rather than the entire length of the axon, because it is jumping from one node to the next rather than moving steadily down the length of the axon.

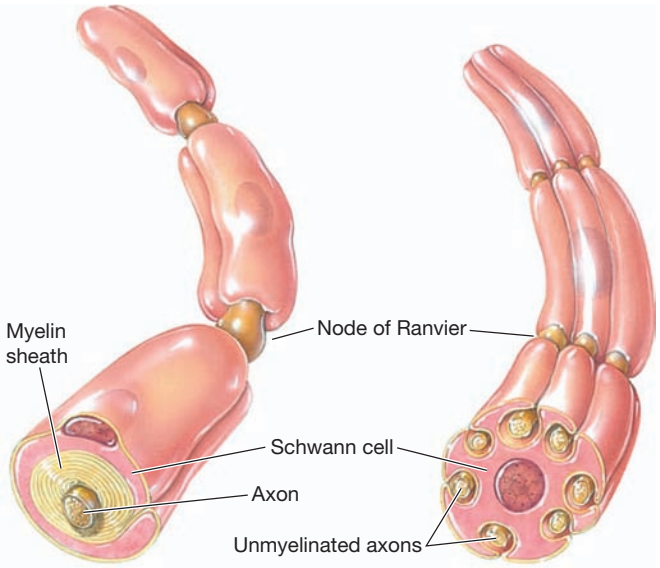
myelin White lipids and phospholipids wrapped around neural processes that aid in faster transmission.

In the PNS, the neuroglial cells responsible for myelination are called **Schwann cells**, as shown in Figure 7.8. These cells wrap around the axon, providing a covering of phospholipids. Schwann cells also aid in regeneration of neural axons. If the axon is damaged, the Schwann cells remain in place, providing a tube through which the regenerating axon can grow. In this way, the axon terminus remains in association with the same muscular or glandular cells when it regenerates after being severed. As you can see in Figure 7.8, there are gaps where the axon is not covered by myelin—these are called *Nodes of Ranvier*.

Schwann cells are not present in the CNS, where myelin is provided by **oligodendrocytes**. Oligodendrocytes are large cells with branching appendages that touch and

Schwann cell • Figure 7.8

Schwann cells individually wrap and protect the delicate and often extremely long axons of PNS neurons. They secrete compounds that aid in the regeneration of severed neuronal processes, as sometimes happens when we receive a deep wound.



a. Schwann cell providing myelin sheath for a single axon

b. Schwann cell protecting but not myelinating many PNS axons

protect many axons. If an axon is damaged in the CNS, the oligodendrocyte retreats, leaving no tube or pathway to aid in axonal regrowth. This is partially why spinal-cord injuries are usually permanent.

Although PNS neurons can recover from some damage, neurons in neither the PNS nor the CNS can regenerate if the cell body is damaged. Axons will regenerate only if they are damaged beyond the axon hillock. As far as we know, new neurons do not form in adult CNS tissue with the exception of one small area of the brain called the hippocampus. Interestingly, some forms of depression seem to be linked to the inability to generate new neurons in this area. For the most part, when a CNS neuron is damaged beyond repair, it is lost.

Synapses Separate One Neuron from Another, and Neurotransmitters Bridge the Gap

Action potentials move along the neural membrane as a local change in voltage. Ions flow back and forth across the membrane as gated channels open and close, causing the alteration in voltage associated with the action potential.

At the **terminal bulb**, however, the impulse must be transferred to the next neuron in line; there is no membrane to carry it. Neurons do not physically touch one another; instead, they are separated by a gap called a synapse, as shown in **Figure 7.9**. Neurotransmitters released from the terminal bulb diffuse into the synapse, just as they do at the neuromuscular junction. They traverse this space, called the synaptic cleft, by simple diffusion. Neurotransmitters leave the **presynaptic neuron** and diffuse toward the **postsynaptic neuron**, where they settle on receptors and initiate a reaction. (See *What a Scientist Sees: Your Brain on Alcohol.*)

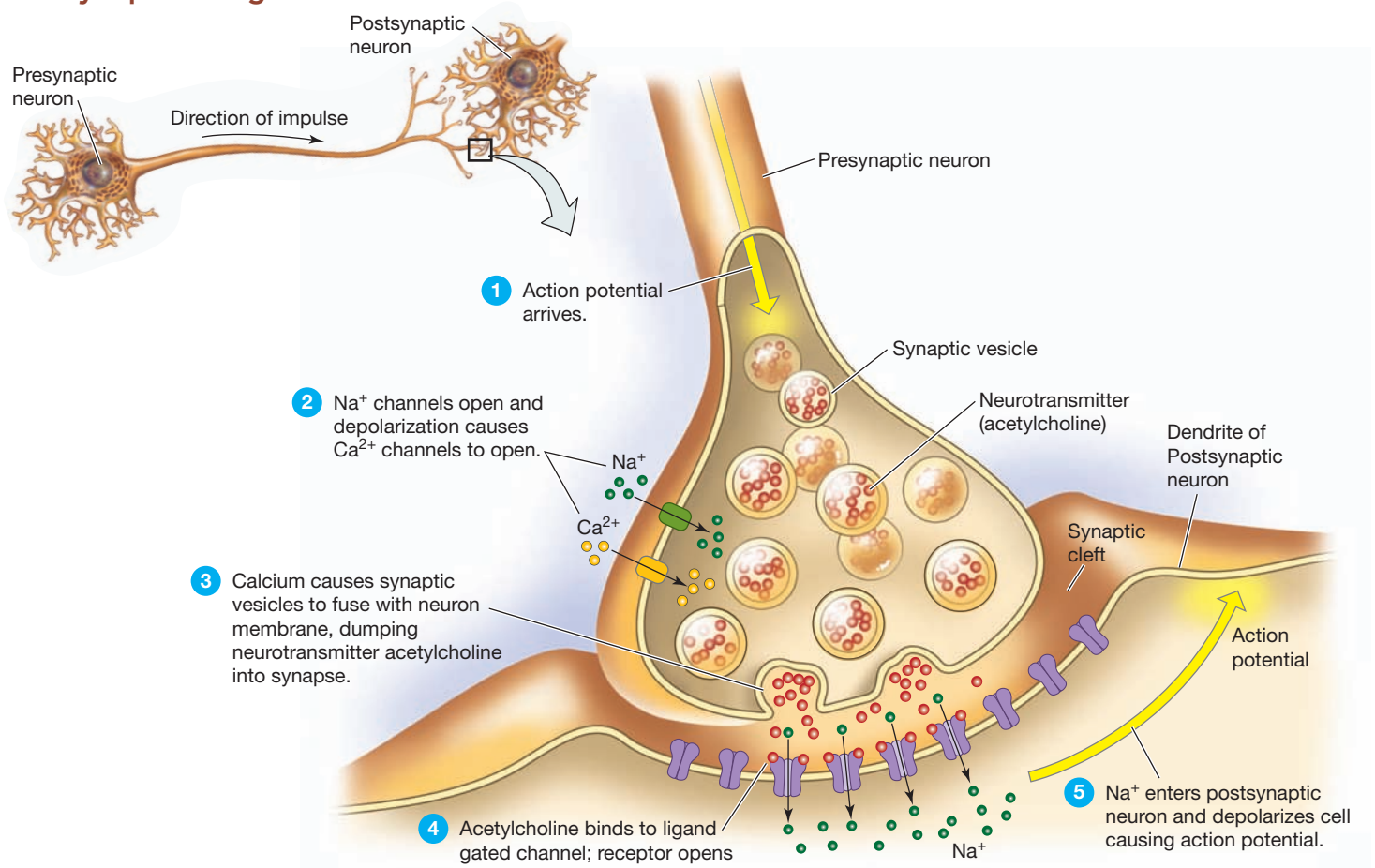
terminal bulb The swollen terminal end of the axon that releases neurotransmitters into the synapse.

presynaptic neuron The neuron that lies before the synapse, whose axon leads to the synapse.

postsynaptic neuron The neuron that begins after passing the synapse.

Neurotransmitters carry the message across the synapse. Neurotransmitters are specific chemicals that carry an impulse across a synaptic cleft (**Table 7.3**).

The synapse • Figure 7.9



WHAT A SCIENTIST SEES

NATIONAL GEOGRAPHIC

Your Brain on Alcohol

To many, this young man looks like he has had too much to drink. A scientist sees a young man flirting with neural damage.

Alcohol is a depressant, causing changes in the functioning of the brain at the synapse. Normally, GABA, an inhibitor, is not found in great quantities in the synapses of the brain. When alcohol is introduced, the neurons that release GABA are no longer controlled, and GABA floods the system, slowing response time and causing many of the effects we associate with drunkenness.

Recent studies have shown that alcohol damages the communication between neurons by disrupting the structure of the neuronal cell membrane. This in turn leads to abnormal electrical signals, which may initiate the inappropriate release of GABA. While there is debate over whether or not alcohol kills neurons outright, the damage it causes can lead to permanent damage to the nervous system.

Think Critically

1. It is very easy to drink more alcohol than the body can properly process. Knowing that alcohol is a depressant, can you suggest what might lead to someone drinking too much?
2. Given the potentially permanent consequences, why do you think alcohol remains such a popular drug in American culture?

Neurotransmitters Table 7.3

Class	Name	Location	Effects
Acetylcholine	Acetylcholine	Throughout CNS and PNS, neuromuscular junctions, parasympathetic division	Contracts muscle, causes glandular secretions, general parasympathetic functions
Biogenic amine	Norepinephrine	Hypothalamus, brain stem, cerebellum, spinal cord, cerebral cortex, and most sympathetic division junctions	Attention, consciousness, control of body temperature
Biogenic amine	Epinephrine	Thalamus, hypothalamus, midbrain, spinal cord	Uncertain, but thought to be similar to norepinephrine
Biogenic amine	Dopamine	Hypothalamus, midbrain, limbic system, cerebral cortex, retina	Regulates subconscious motor functions, emotional responses, addictive behaviors, and pleasurable experiences
Biogenic amine	Serotonin	Hypothalamus, limbic system, cerebellum, spinal cord	Maintains emotional states, moods, and body temperature
Biogenic amine	Histamine	Hypothalamus	Sexual arousal, pain threshold, thirst, and blood pressure control
Amino acid	Glutamate	Cerebral cortex and brain stem	Excitatory, aids in memory and learning
Amino acid	GABA	Cerebral cortex	Inhibitory, shows potential as an anti-anxiety drug
Neuropeptide	Substance P	Spinal cord, hypothalamus, digestive tract	Pain sensation, controls digestive functions
Neuropeptide	Neuropeptide Y	Hypothalamus	Stimulates appetite and food intake
Opioids	Endorphins and enkephalins	Thalamus, hypothalamus, brain stem	Pain control, behavioral effects

We currently have identified and studied more than 45 neurotransmitters, each with a slightly different effect on the postsynaptic neuron. The most common neurotransmitters are **acetylcholine** (ACh) and **norepinephrine** (NE). As described in Chapter 6, ACh stimulates muscle contractions when picked up by receptors on the muscle cell membrane. Once released, it is broken down quite rapidly by the enzyme **acetylcholinesterase**. ACh is present on the muscle cell and in the synapse for approximately 20 milliseconds.

Norepinephrine (NE) is responsible for the excited rush we experience during tense situations. NE, unlike ACh, is mostly reabsorbed by the presynaptic neuron instead of being broken down. Reabsorption takes longer, so NE can remain effective for 1 to 2 seconds at a time. Drugs also affect neurons at their synapse.

HEALTH, WELLNESS, AND DISEASE

What Causes Drug Addiction?

Addiction, in its barest form, is the inability to stop a psychologically or physically habit-forming behavior without suffering severe withdrawal. Often addiction causes bodily harm, permanently damaging cells and preventing normal homeostatic functioning. Substances that trigger addiction include nicotine, caffeine, alcohol, and a host of "recreational drugs" such as cocaine, morphine, and barbiturates. Some recreational drugs—for example, ice (crystal methamphetamine) and heroin—are so strongly addictive that dependency may begin with the first contact. Others, like alcohol and nicotine, require chronic exposure to stimulate addiction, and even then some individuals will not suffer addiction. This raises the question, What is happening within the brain to cause addiction?

Most of the highly addictive drugs stimulate what is referred to as the reward circuit of the brain. This area is found within the limbic system, where it links structures that control our ability to feel pleasure. Activities that stimulate the reward circuit release the neurotransmitter dopamine, resulting in feelings of euphoria. Life-sustaining activities such as eating stimulate the reward circuit, ensuring that they will be repeated. Recreational drugs often stimulate this same circuit, flooding the area with dopamine or a dopamine mimic.

A second route of addiction related to the body's stress response has been uncovered recently. Circulating hormones that are usually found in high concentration only during acute stress also increase during chronic drug abuse. The effect of these hormones is to stimulate the amygdala, the portion of the brain involved in emotional learning and fear conditioning. It is hypothesized that this emotional attachment strongly triggers addiction and addictive behaviors.

A final piece in the science of addiction deals with neuronal changes with repeated drug use. Neuroplasticity describes the physical changes in neuron synapses that occur normally during learning and memory. Drug addiction is characterized by one of two types of permanent neuroplasticity: long-term potentiation or long-term depression. In both cases, neuron communication is permanently altered so that the addicting substance is required in order for these neurons to function.

NATIONAL GEOGRAPHIC

Graded Responses Create Fine Neural Control

Action potentials are "all or nothing" events, meaning that once the threshold is reached, the nerve will fire completely. Because a single neuron cannot create a partial action potential, we vary the strength of nervous stimulation by changing the number of neurons that are firing.

Graded responses can be obtained by **hyperpolarizing** or **depolarizing** individual neural membranes. A hyperpolarized neuron requires a larger stimulus to reach threshold and begin an action potential. A depolarized neuron is the opposite: It requires less of a "kick" to begin an action potential, because its resting potential is closer to the action potential threshold. Once threshold is reached, however, the neuron generates an action potential that is indistinguishable from any other action potential.

The hyperpolarized and depolarized neurons result from alterations in the resting membrane potential of postsynaptic neurons. Two types of postsynaptic potential can be developed. **Excitatory postsynaptic potentials** (EPSPs) cause slight depolarization of the neuron. The membrane potential is already closer to threshold, so a smaller stimulus is needed to begin the action potential. Think of being in a frustrating situation: Maybe you are trying to study for a human biology test while your roommates are listening to music with a driving beat. The longer this goes on, the more frustrated you become. When your roommate asks if you want something to eat, you snap at her. Normally, having to answer this question would not elicit such a reaction, but when you are already angry, it does. This quick reaction to a smaller stimulus mimics an EPSP.

Inhibitory postsynaptic potentials (IPSPs) cause the opposite reaction in the postsynaptic neuron. IPSPs hyperpolarize the neuron, meaning the membrane potential is further from that needed to generate an action potential, so a larger stimulus is required to begin an action potential. Using the above example, if you were wearing headphones with relaxing music, you could block out the noise, and your roommate would need to tap your shoulder to get your attention. She would need to raise the input level to receive the normal response. Many prescription and recreational drugs affect the events of the synapse, as discussed in *Health, Wellness, and Disease: What Causes Drug Addiction?* Such drugs can alter the potential of the pre- and postsynaptic neurons, affect the diffusion of neurotransmitters, or even mimic the effect of the neurotransmitters on the postsynaptic neuron.

CONCEPT CHECK STOP

1. **What** is the difference between action potential and membrane potential?
2. **What** types of channels are found in neuron membranes?
3. **What** are the main steps in an action potential?
4. **What** are the events that occur at a typical synapse?

7.3 The Brain and Spinal Cord Are Central to the Nervous System

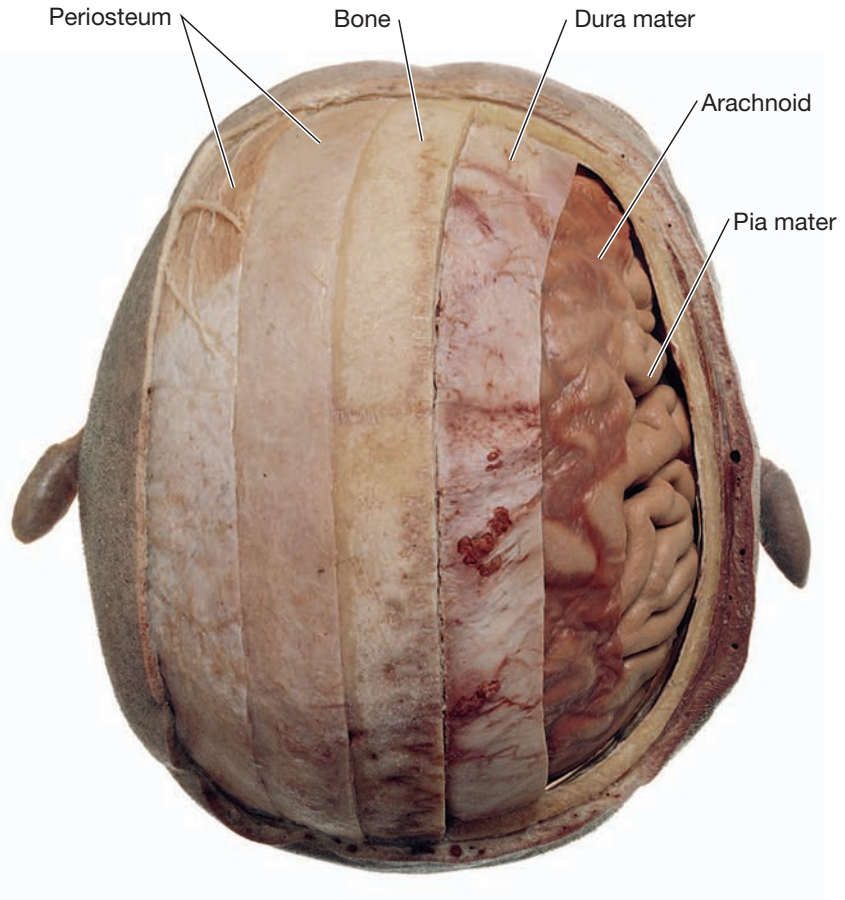
LEARNING OBJECTIVES

1. **Describe** the anatomy and coverings of the brain.
2. **Explain** the functions of the various parts of the brain.
3. **Explore** the anatomy of the spinal cord.
4. **List** the steps in a typical reflex.

The human brain occupies approximately 1,250–1,400 cubic centimeters and weighs about 1,400 grams. In terms of complexity, nothing that we know of in the universe is even close. Although brains look pretty unexciting from the outside, they conceal an amazing level of detail, all of which emerges from just a few types of cells that are specifically and purposefully connected. We'll start our examination of the brain by looking at how it is protected from injury.

Meninges • Figure 7.10

The meninges lie directly under the skull, between the bone and the brain. Here you can see the skin on the left side of the head. The sequential layers visible from left to right are the periosteum of the skull bones, the bone itself, the dura mater, the arachnoid, and the pia mater.



The Meninges and Cerebrospinal Fluid Protect and Nourish the Central Nervous System

The axial skeleton provides bony protection for the CNS. The **meninges** and **cerebrospinal fluid (CSF)**, in turn, protect the CNS from the axial skeleton, providing a soft lining and cushion that nourishes and protects the delicate neural structures. The meninges are a series of three connective tissue coverings between the nervous tissue and the bone that surround and protect the brain and spinal cord, as shown in Figure 7.10. The cerebrospinal fluid within the meninges nourishes the neurons and absorbs shock.

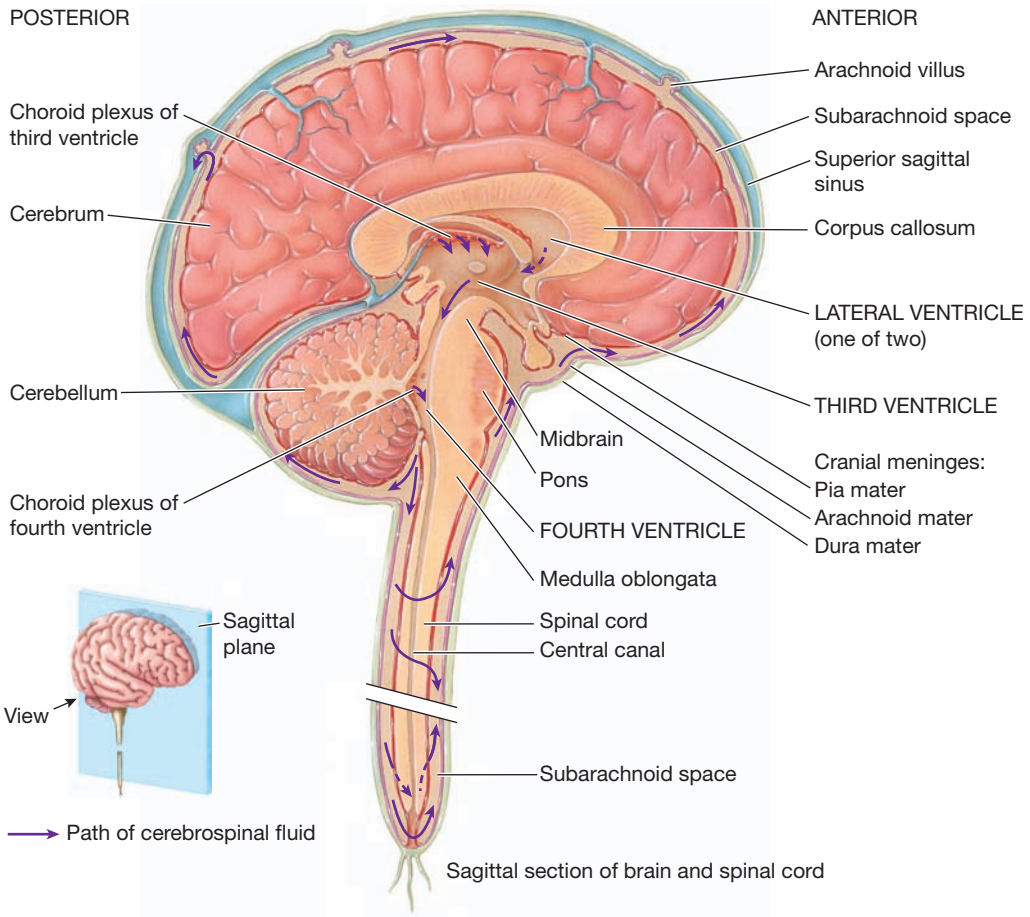
cerebrospinal fluid (CSF) A liquid similar to plasma, but with less dissolved material, that maintains uniform pressure within the brain and spinal cord.

The outer covering of the meninges, called the **dura mater**, is a tough connective tissue layer immediately beneath the skull. Below the dura mater is the **arachnoid**. This layer is thin and fragile and looks like a spider web. Cerebrospinal fluid flows between the strands of the arachnoid. The inner layer of the meninges is called the **pia mater**. This extremely thin layer is attached to the neurons and cannot be peeled off without damaging them.

Meningitis, an inflammation of these three layers of connective tissue, is extremely difficult to treat because the environment of the brain is isolated and controlled, so medications cannot be easily introduced. Meningitis can be life-threatening because the swollen membranes compress the neurons of the brain and spinal cord. Meningitis can be viral or bacterial. Although a new vaccine shows promise in controlling viral outbreaks, at present, viral meningitis has no cure. Physicians merely treat the symptoms and hope that the patient is strong enough to recover after the virus runs its course. Bacterial meningitis causes other concerns. Normal doses of antibiotic are ineffective because they seldom if ever get from the blood to the cerebrospinal fluid of the brain and on to the meninges. It is difficult to prescribe the

CSF formation and flow • Figure 7.11

Each ventricle contains a choroid plexus, which forms CSF. CSF flows throughout the central nervous system, starting in the ventricles and flowing down toward the spinal cord. It flows down the central canal of the spinal cord, then up the outside of the cord, and around the outside of the brain. CSF is absorbed into the bloodstream in the subarachnoid space.



proper amount of antibiotic—too little will not reach the infection, and too much can kill the patient.

Cerebrospinal fluid provides a constant environment for the central nervous system. Every time you move your head, your brain floats within the cranium. When you lift your head from your pillow in the morning, the brain sloshes toward the occipital bone. Because fluid is noncompressible, the CSF around the brain prevents the fragile surface of the brain from striking the cranium. Otherwise, the delicate outer portion of the brain would bang against the bones every time you moved your head, destroying neural connections and ultimately the tissue itself.

Ventricles make cerebrospinal fluid. The brain may look like a solid mass of nervous tissue, but nothing could be further from the truth. Four rather large cavities in the brain are filled with CSF. These cavities are literally holes in your head, but we call them ventricles, shown in Figure 7.11.

CSF is continuously produced and absorbed, creating a constant flow. If drainage back to the blood and the heart gets blocked, CSF builds up within the brain, adding a watery fluid under the skull that is rightly named hydrocephaly ("water head"). In infants whose skull bones have not yet fused, hydrocephaly forces the entire cranial cavity to expand at the fontanels. Once the skull has ossified, there are no fontanels, and hydrocephaly compresses the neurons of the cortex, effectively shutting down parts of the brain. This condition can be corrected by surgically implanting a shunt to drain the excess fluid.

CSF formation helps maintain the **blood-brain barrier**, which permits only certain ions and nutrients to cross the vessels of the choroid plexus, resulting in a controlled environment for CNS neurons. Bacteria and viruses thus have difficulty entering the brain. Unfortunately, when bacteria do enter, they are difficult to treat, because the blood-brain barrier also keeps most antibiotics out.

The Brain Has Four Main Parts

A close look at the brain reveals four major parts—see Figure 7.12:

- the brain stem
- the diencephalon
- the cerebellum
- the cerebrum

Although the entire brain is basically involved in the integration of sensory input and motor responses, each section has different roles.

The brain stem is an ancient root of life. The brain stem contains vital centers that regulate heart rate, breathing, and blood pressure. The brain stem is the portion of the brain that is closest—anatomically and physiologically—to the spinal cord. The mid brain, **medulla oblongata**, and **pons** make up the brain stem.

medulla oblongata Portion of the brain stem immediately adjacent to the spinal cord, associated with heart rate, breathing controls, and blood pressure.

pons The area superior to the medulla oblongata, involved in transfer of information and respiratory reflexes.

The medulla oblongata contains the vital centers of the brain stem associated with heart rate, respiratory function, and blood pressure. These centers, found in many animals, indicate that the medulla oblongata evolved in ancient times. The medulla oblongata also contains reflex centers for sneezing, coughing, hiccupping, and swallowing. Motor impulses generated in the higher centers of the brain travel through the medulla oblongata on their way to the PNS.

You may have heard that the right side of the brain controls the left side of the body, and vice versa. This is basically true, because 80% of the motor information from the right side of the brain enters the medulla oblongata and crosses to the left side before leaving the CNS. The crossing of these tracts is visible on the anterior surface of the medulla oblongata.

tracts Axons and/or dendrites with a common origin, destination, and function.

The pons focuses on respiration. Most of the pons is composed of **tracts** that carry information up to the brain, down from the brain to the spinal cord, or laterally from the pons to the cerebellum. The only vital center found in the pons is related to respiratory reflex. The **apneustic** and **pneumotaxic** reflexes begin in the pons. The apneustic center triggers breathing even when we consciously hold the diaphragm still. Despite the threats of countless children, you cannot hold your breath until you die. If you tried your hardest, you would eventually pass out, and the apneustic center would immediately restart your breathing. The pneumotaxic center works oppositely, because it is charged with preventing overinflation of the lungs. When stretch receptors in the lungs are stimulated, the pneumotaxic center sends a motor response, causing you to exhale.

The cerebellum focuses on muscles and movement. Posterior to the brain stem, we see something that looks like a smaller brain hanging off the back of the brain. This small, round structure is the cerebellum, shown in Figure 7.12. It has two main functions: maintaining muscle tone, posture, and balance; and fine-tuning conscious and unconscious movements directed by the cerebrum. Although we walk without thinking, the process requires exact coordination. That smooth gait, with its leg lifts and counterbalancing arm swings, is directed by the cerebellum.

One job of the cerebellum is to understand where the limbs are located, using proprioception. This sensory capability allows you to lift your legs and move them forward without glancing at them, because your brain knows where your feet are at all times. The nervous pathways associated with proprioception run from the muscles and joints to the cerebellum.

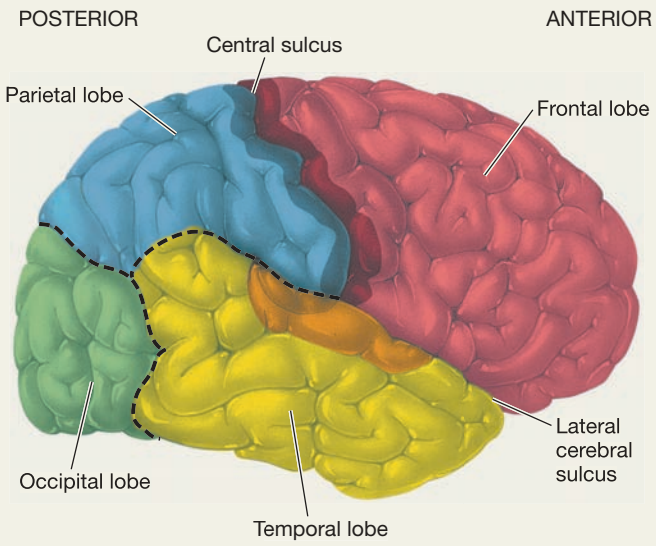
The cerebellum is also important in learning motor skills. Riding a bike, learning to swim, or even learning new information through repeatedly writing notes are all examples of cerebellar learning. New research indicates that the cerebellum may also play a role in sensory integration by receiving input from sensory neurons and directing it to inner portions of the cerebrum. Abnormal cerebellar anatomy has been detected in autistic children, suggesting a link between cerebellar function and autism. Autism is discussed in *Ethics and Issues: Autism: Genetics or Environment?*

The human brain has four parts: the brain stem, the diencephalon, the cerebellum, and the cerebrum. Different views highlight different parts.

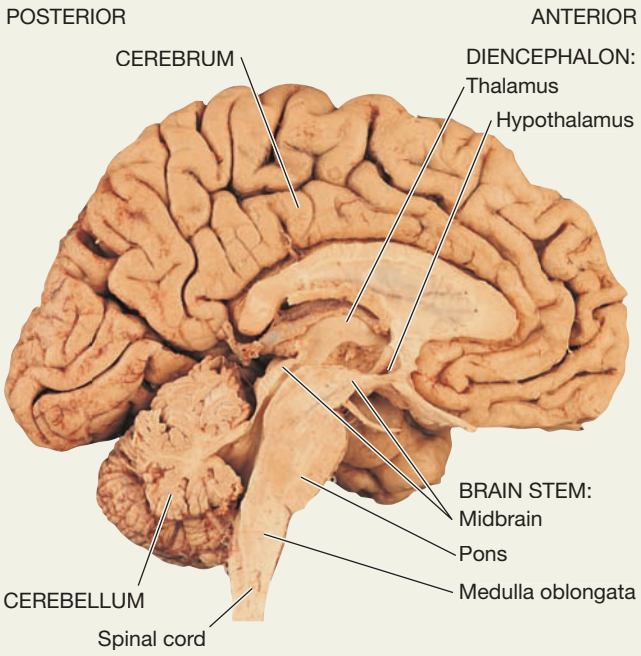
WILEY PLUS Video

a. Colorized brain scan

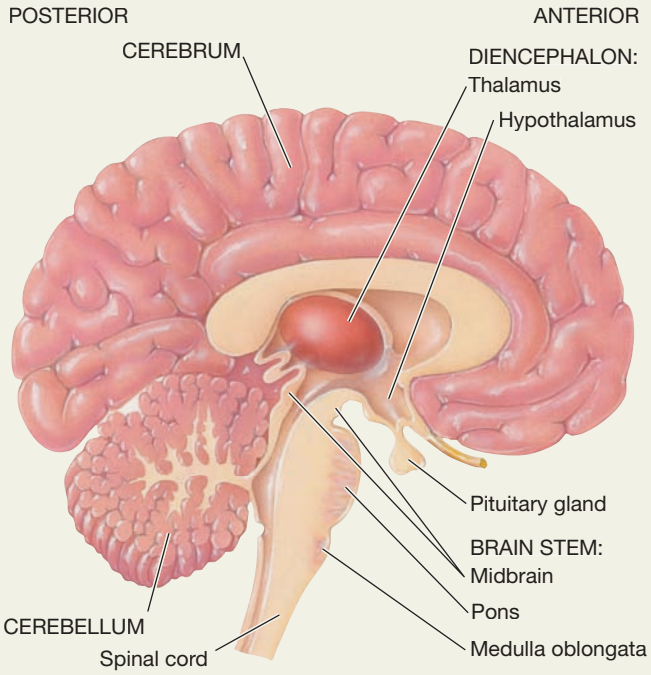
b. Cerebrum with lobes



c. Sagittal section (vertical cross section), medial view, photo



d. Sagittal section (vertical cross section), medial view, drawing



NATIONAL GEOGRAPHIC

ETHICS AND ISSUES

Autism: Genetics or Environment?

Since the late 1990s, a small but vocal group of parents of and advocates for autistic children has argued that a link exists between childhood vaccination and the steady increase in autism in the United States and Europe, as shown in the graph. However, the role that genetics or environment plays in the development of autism remains unclear.

All children with autism have difficulty in social interaction and communication. While some are intelligent, others are mentally impaired. They may be highly sensitive to touch, engage in repetitive behaviors, or have obsessive interests. Many parents say they "knew" from infancy that their child was different—he or she didn't make eye contact, didn't like to be cuddled, or was late achieving various developmental milestones.

The age range during which most diagnoses of either classical autism or Asperger syndrome are made coincides with the range during which children receive a number of vaccinations (18 months to 5 years). For parents whose child reaches developmental milestones appropriately, then begins to regress at the same time that he or she receives vaccinations, there is an obvious question of cause and effect. The vaccination–autism link was first suggested in England in 1998, when Andrew Wakefield and colleagues published an article describing 12 children with ASD, 8 of whom (according to their parents' recollections) developed these symptoms shortly after receiving the measles, mumps, and rubella (German measles) vaccination (MMR). The authors acknowledged that no causal link could be determined from such a small sample and retrospective reporting.

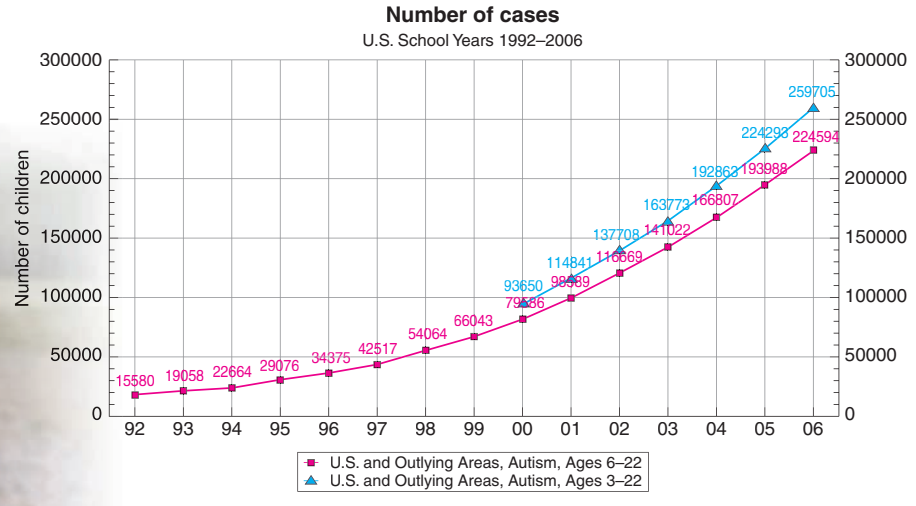
Despite this, the impact of Wakefield's results in the community at large was tremendous and seemed a validation of what parents and advocates had suspected. However, in 2010, Britain's General Medical Council ruled that Wakefield had dishonestly misled the scientific community. Wakefield's work with children inoculated with the MMR vaccine was described by the editor of The Lancet, Richard Horton, as "fatally flawed." *The Lancet* issued a rare apology for the published paper.

"We wish to make it clear that in this paper no causal link was established between (the) vaccine and autism, as the data were insufficient. However, the possibility of such a link was raised, and consequent events have had major implications for public health. In view of this, we consider now is the appropriate time that we should together formally retract the interpretation placed upon these findings in the paper, according to precedent."

Critical Reasoning Issues Despite the retraction of Wakefield's paper, the damage had been done. An autism–vaccination link had been `found' as far as the public was concerned. Public health would suffer because of doubts about the safety of vaccines. Doctors in the US and the UK are beginning to see childhood diseases that had many years ago almost vanished for the population.

In the United States anti-vaccination advocates argued that thimerosal was the "causative" agent of autism. Thimerosal is a mercury-containing preservative used from the 1930's until 2000 in many vaccines. Examples of vaccines with thimerosal included those for diphtheria, tetanus, and polio (DtaP), hepatitis B, and haemophilus influenza type B (HiB), three vaccines that are given to infants. Even after thimerosal was removed from these vaccines, however, autism rates continued to rise. To date, scientific evidence does not support a direct cause-and-effect relationship between autism and vaccinations, and yet the autism–vaccination connection remains in people's mindset. This is partly because of our "natural" but flawed tendency to link chronology with a cause-effect ("if after X, then Y because") as well as people assuming that anecdotal information ("medical gossip" so to speak) are as valid as large controlled samplings of a population.

Increase of U.S. autism cases



Think Critically

Scan news stories about current research. Can you find examples of a few anecdotes being used instead of large controlled studies to make a point?

The diencephalon is a relay center. The diencephalon includes the central portion of the brain and functions mainly as a relay center for sensory information from the body and motor responses from the cerebrum. Within this portion of the brain, conscious and unconscious sensory information and motor commands are integrated. Centers for visual and auditory startle reflexes are located here. The auditory reflex causes you to "jump" when you hear a car backfire. The visual reflex can also cause you to jump when you are focused on reading or studying and something flits by your peripheral vision. If you jump and rapidly turn your head to catch that fleeting vision, you've had a visual reflex.

The **thalamus** and **hypothalamus** are also located in the diencephalon. The thalamus is a relay station for most incoming sensory information. Stimuli are sent from the thalamus to the appropriate portions of the cerebrum. The **limbic system**, which is responsible for our emotions, communicates with the anterior portion of the thalamus. This communication forms a physical link between incoming sensory information and emotions. See Figure 7.13.

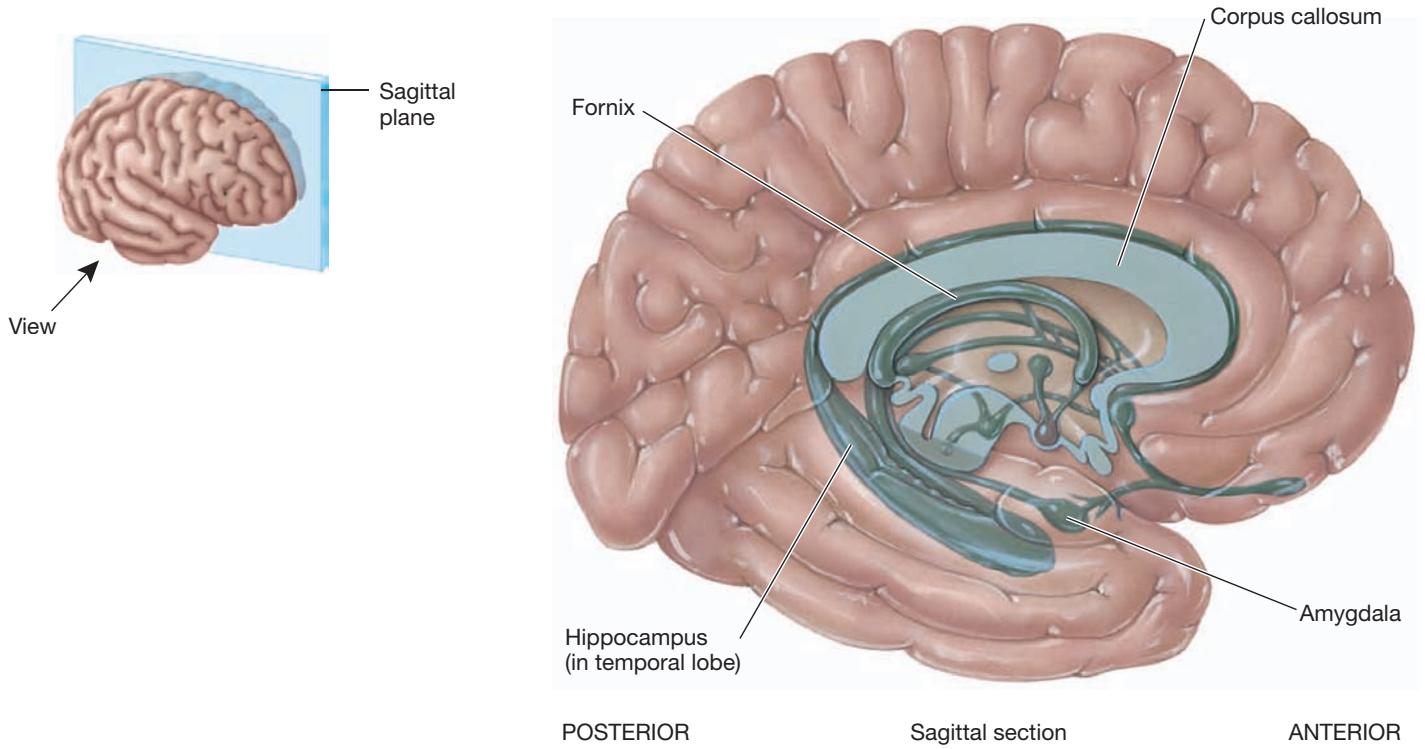
The hypothalamus is, as the name implies, below the thalamus. It secretes hormones that control the anterior pituitary gland, monitor water balance, and stimulate smooth muscle contraction. The hypothalamus also regulates our circadian rhythm, body temperature, heart rate, and blood pressure.

The Cerebrum Is a Central Processing Center

The cerebrum is the largest portion of the brain and is shown in Figure 7.14 on the next page. In the cerebrum, information is processed and integrated and appropriate responses are generated. The cerebrum contacts all other parts of the brain and is our center for higher thought processes. It is here that we learn, remember, and plan activities. See *I Wonder... An Amoeba that Eats Human Brains?* to learn how important brain functioning is to our health.

Learning is a type of memory. Understanding how we learn is one of the toughest challenges in neuroscience. Brains are sometimes compared to computers, but although it's easy to point to the place where a hard drive stores certain information, that is seldom possible in the brain. The brain stores information here and there, in complex, thread-like networks of neurons. Our learned ability to speak, for example, is stored separately from our memory

The limbic system • Figure 7.13



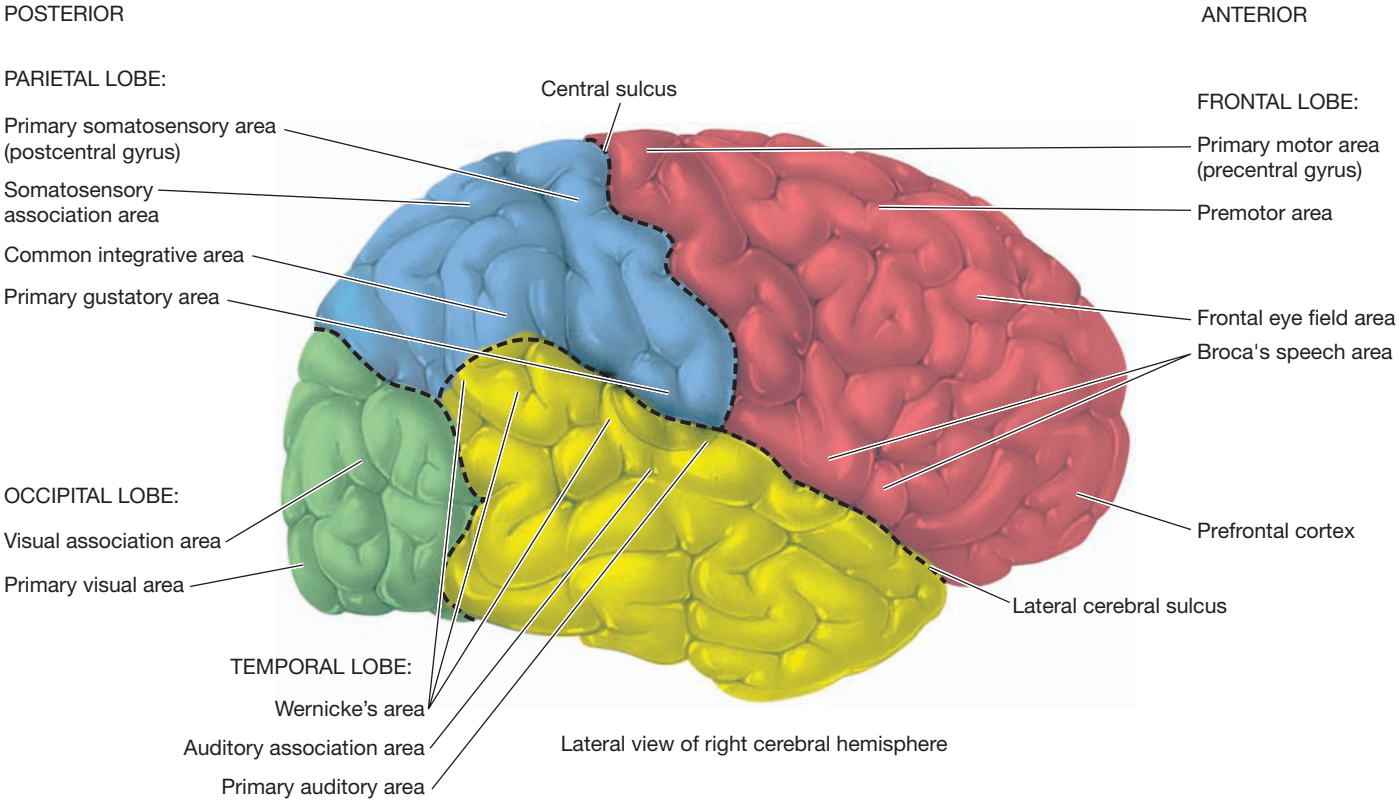
I WONDER...

An Amoeba that Eats Human Brains? That Just Can't Be True.

It sounds like the plot of a low-budget movie, but in fact there are documented cases of people dying from being infected with just such an amoeba. The CDC has confirmed 23 such infections between 1995 and 2004, and in 2007 six more deaths were attributed to it. This pathogenic amoeba is a member of the genus *Naegleria*, a free-living amoeba found in water and soil. Only one species of *Naegleria* infects humans, *N. fowleri*. This protist lives in warm bodies of freshwater. It is a heat-loving organism, so as water temperatures increase, so too does the amoeba population. It is found sliding along the bottom, eating bacteria and alga. If the bottom gets stirred up, the amoeba floats. Infection occurs when a droplet of water carrying one of them enters the nasal cavity. The amoeba must land near the olfactory nerve. It crawls to the nerve and digests its way to the brain. Symptoms include headache, fever, vomiting, and stiff neck. Horribly, death can result in just two weeks.

Of course, not every summer dip will result in death. In order to attack, this amoeba must be forced far into the nasal cavity. This can happen as water enters the nasal cavities during rough play, such as "cannon-balling." Merely getting your nose wet during swimming is not considered dangerous. The answer to the question above is yes, these horror stories are real. Even though it may not be comfortable, plug your nose before diving in.

Cerebrum with lobes and their general functions indicated • Figure 7.14



Lateral view of right cerebral hemisphere

of last year's birthday party, and both are stored separately from our ability to paddle a canoe or whistle a song.

Learning is a type of memory, and memory occurs in three phases:

- **Immediate memory** prevents us from being bewildered by maintaining information in our consciousness so that we know, for example, where we are.
- **Short-term memory** helps us carry out tasks—keeping a conversation going or remembering why we are writing a letter. Although much of our short-term memory is quickly erased, some of it gets adopted in long-term memory.
- **Long-term memory** can survive for life, or it can fade, but it is what many people mean when they say "memory."

Scientists believe these three types of memory may exist in different parts of the brain.

Several types of change occur when the brain remembers something, but we call them all "neural plasticity," meaning changes in the brain that alter its ability to do something. The neural plasticity associated with learning has several components. For example, during learning, specific proteins are synthesized in the brain (we know this is true because when we block protein synthesis, we block learning). Synapses change in neural pathways so that impulses can travel through them faster and more easily—a change we call potentiation. When we learn to ride a bike, for example, the neural pathways that tell us to steer to avoid falling are potentiated. The next time we ride, these reactions happen faster and take less conscious effort, until they eventually are triggered automatically whenever we ride a bike.

Neural plasticity also changes the dendrites—the neural processes that bring impulses to the cell body. Recent studies on teaching skills to rats looked specifically at the rat hippocampus and found that certain ion channels in the membrane at the dendrites become more numerous after only 10 minutes of training.

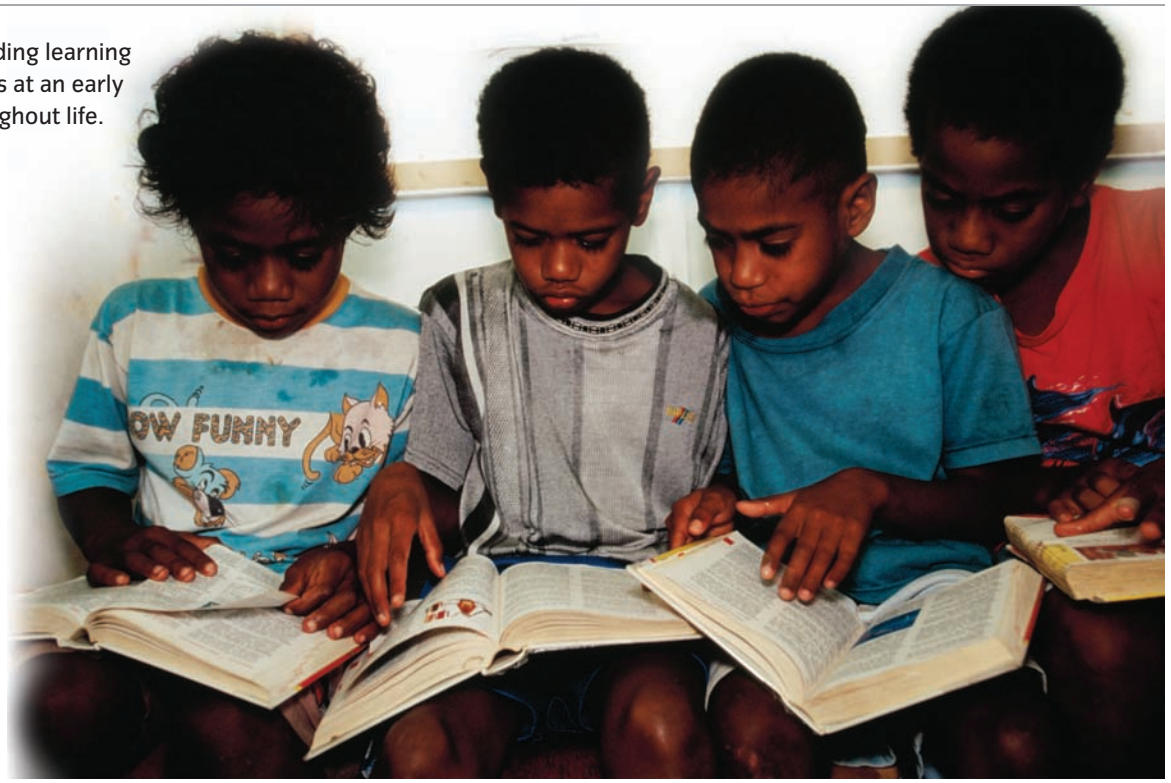
Learning does not exist in a vacuum; the brain's ability to learn is related to what else is going on. Lab studies show that fight-or-flight conditions drastically reduce the ability to learn. People with post-traumatic stress disorder have difficulty learning, probably because of high levels of stress hormones. Emotional stress may even cause amnesia, which can destroy our memory of who we are, without harming the skill of tying a shoe.

Memory and learning, as in **Figure 7.15**, play a critical role at both ends of life. Learning to swim, play guitar, or distinguish the peripheral from the central nervous system may all occur while we are young. In our final years, diseases like Alzheimer's can undo the learning of a lifetime, leaving us bewildered and frustrated over

Figure 7.15

Scholarly learning, including learning to read and study, begins at an early age and continues throughout life.

NATIONAL GEOGRAPHIC



simple tasks we used to accomplish with ease. One final point in our "scratch-the-surface" overview of learning: The topic remains a black hole of neuroscience. Expect to learn a lot more about learning in the years to come.

The surface of the cerebrum has creases or **sulci** that separate individual raised portions called **gyri**. The surface of the cerebrum consists of **gray matter**, whereas the interior is white. Gray matter is mainly cell bodies and nonmyelinated neural processes—in other words, naked axons and dendrites. In the gray matter, connections are made as axons meet dendrites. The cerebral **cortex** is entirely gray matter, folded to provide a larger surface area for these neural connections. It contains billions of cell bodies responsible for sensations, voluntary movements, and thought.

sulci (sulcus)
Shallow grooves on the surface of the brain.

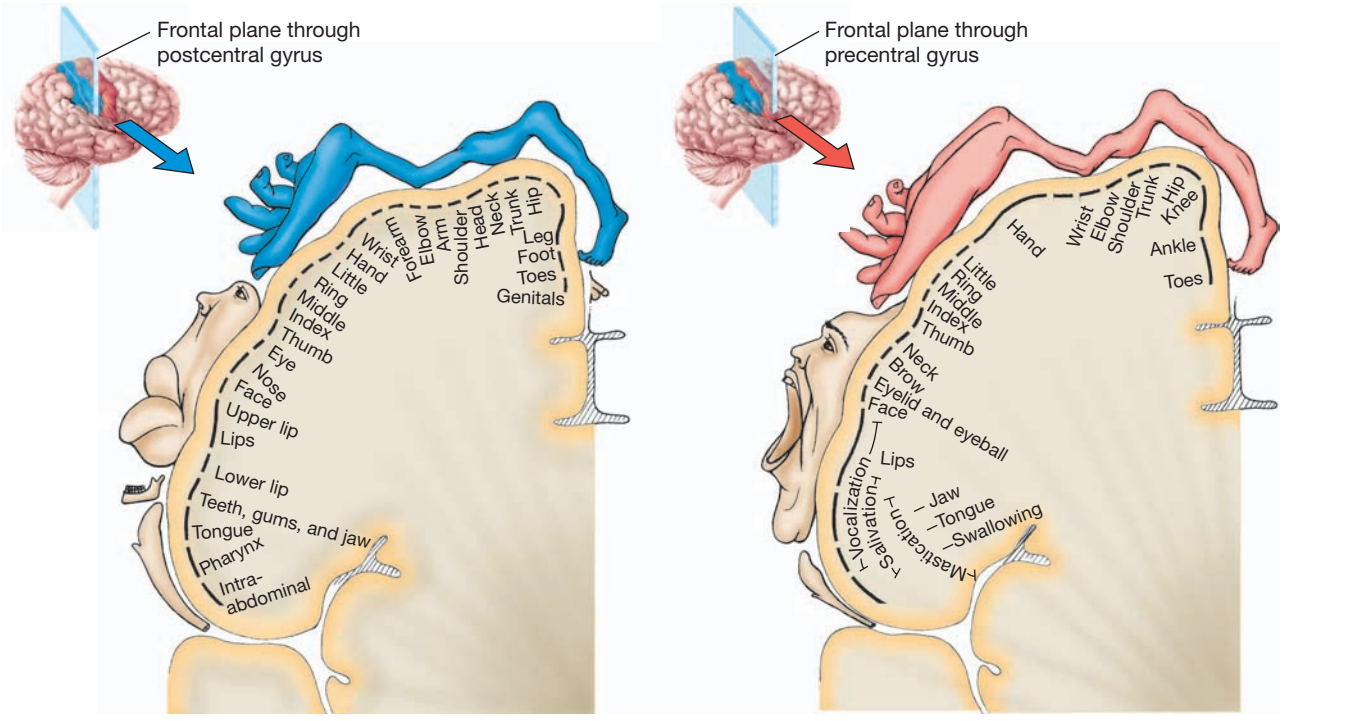
gyri (gyrus)
Elevations separating individual sulci; the bumps on the brain.

cortex Thin outer layer of any organ.

The white matter inside the cerebrum contains myelinated axons that carry information to the spinal cord or other areas of the brain. Myelinated axons are covered in lipids, giving this tissue its characteristic white appearance and allowing for faster impulse transmission. Information is passed from one area of the brain to another via tracts of white matter.

The cerebral hemispheres are homes of logic and artistry. The cerebrum has two hemispheres that are quite similar anatomically. Both hemispheres are divided into lobes with general functions assigned to each. For example, the occipital lobe is where vision is interpreted, and the frontal lobe is involved in conscious thought processes. The cortex of each lobe has motor areas, sensory areas, and **association** areas that integrate new information with stored memories. The **primary motor** area, in the frontal lobe just in front of the central sulcus, formulates voluntary motor commands. Each portion of the body is represented in the primary motor area. The more control we have over movements of a particular body part, the larger is the section of the primary motor area devoted to it, as seen in the **homunculus** diagram (Figure 7.16).

Sensory homunculus and motor homunculus • Figure 7.16



a. Frontal section of primary somatosensory area in right cerebral hemisphere

b. Frontal section of primary motor area in right cerebral hemisphere

Sensory information from the skin and skeletal muscles is received in the primary somatosensory area of the cortex, just behind the primary motor area. As with the primary motor area, sensations from each body part go to a specific segment of this gyrus. The larger the segment of primary somatosensory area devoted to the body part, the more sensory receptors are found in that part. Interestingly, when any of the nerves along these sensory pathways are stimulated, the brain interprets the sensation as coming from the organ at the distal end of the pathway, regardless of the source of the stimulation. The result is called **referred pain**, which also occurs when we interpret a painful stimulus from an internal organ as pain in our skin or surface organs. This referral may happen because the visceral sensory pathways often join with or cross cutaneous sensory pathways in the spinal cord. When the pain stimulus reaches the brain, it is interpreted as coming from the skin, which is the usual site of injury. A typical example is the pain of appendicitis. Although the appendix lies in the lower right abdomen, appendicitis pain is usually described as located right behind the umbilicus, or belly button.

A few specialized motor actions are governed by areas outside the primary motor area. The formation of words, for example, is organized in **Broca's area**, on the left frontal lobe.

The left and right cerebral hemispheres are distinct in some important ways. In most people, the right hemisphere analyzes sensory input, recognizes faces, and functions in spatial relationships. Emotional interpretation of conversation is a function of the right hemisphere. When you hear someone say, "that's just great," your right hemisphere determines whether the speaker was actually impressed or speaking sarcastically. The left hemisphere usually includes the general language interpretation and speech centers, and it controls writing and speaking. The left hemisphere is more active during mathematical calculations, categorizing items, and making logical decisions, leading some to call it the "dominant" or "categorical" hemisphere.

special senses The five senses of the body: hearing, vision, taste, smell, and balance.

Special senses (see Chapter 8) are integrated in specific areas of the cerebral cortex. For example, the entire occipital lobe is devoted to visual interpretation. Auditory interpretation occurs in the primary auditory area of the temporal lobe. We even have a primary taste area in the parietal lobes that permits us to differentiate the taste of chocolate from that of coffee. No word yet on how that works with mocha java.

Association areas link information together. Association areas of the cerebral cortex integrate and coordinate information from many sources. For example, the somatosensory association area processes sensory information from the skin and muscles. The visual association area associates new visual information with stored visual images. The auditory association area does the same thing with new auditory information.

Although we can assign functions to each part of the brain, the various parts do not function alone. The brain is a network of incomprehensible complexity. Stimuli are integrated throughout the cortex, and responses are generated from many areas. The left and right sides of the brain connect through the transverse tracts of the corpus callosum, sharing information and generating different responses. In this way, despite **hemispheric lateralization** of some tasks, the entire cerebrum is aware of incoming sensory information as well as outgoing motor responses.

hemispheric lateralization The isolation of a task to either the left or right hemisphere of the cerebrum.

The Reticular Activating System Is the Brain's Alarm Clock

The **reticular formation** serves as an important connection between various parts of the brain. This series of **nuclei** and tracts extends throughout the brain, receiving sensory information, parceling it to the higher centers, and directing motor responses to the appropriate body areas. The **reticular activating system** (RAS) is a portion of the reticular formation that is important in maintaining alertness. Look around the next time you are trapped listening to a long-winded lecture. If your reticular activating system is doing its job, you will remain alert and attentive. However, you might see some people whose RAS is not working so well. Their heads will be drooping; they might even be napping.

nuclei Areas of concentrated neuronal cell bodies in the brain.

The RAS may also be important in our ability to learn. One symptom of **Attention Deficit Hyperactivity**

Common mental disorders Table 7.4

Class of disorder	Common types	Symptoms	Treatment
Anxiety disorders	Phobias	Extreme fear or dread	Medications, cognitive and behavioral therapy
	Panic disorders	Sudden intense feelings of terror for no apparent reason	Medications, cognitive and behavioral therapy
	Obsessive compulsive disorder	Anxiety coping strategies that include repetitive actions or words or ritualistic behaviors	Medications, cognitive and behavioral therapy
Mood disorders	Depression and bipolar disorders	Depression: extreme sadness, sleeping or eating disturbances, changes in activity or energy levels. Bipolar disorder: violent mood swings	Psychotherapy, antidepressants, lithium
Schizophrenia	Schizophrenia	Chemical imbalances in the brain that lead to hallucinations, delusions, withdrawal, poor speech and reasoning	Prescription antipsychotic medications, such as Haloperidol (Haldol) and Loxitane
Dementias	Alzheimer's	Loss of mental function and memory, decline in physical abilities	Increased nursing care
Eating disorders	Anorexia nervosa	Preoccupation with food and unnatural fear of becoming fat, self-starvation or over-exercising	Psychotherapy, lifestyle changes
	Bulimia	Bingeing and purging, cycles of huge caloric intake, with self-induced vomiting	Psychotherapy, lifestyle change

Disorder (ADHD) is the inability to filter out extraneous noises and focus on what is important. The RAS is responsible for this filtering, allowing you to study while the radio is on. It is possible that ADHD is partly due to poor function of the RAS.

Humans suffer from many other mental disorders. Table 7.4 gives some information on the most common of these ailments.

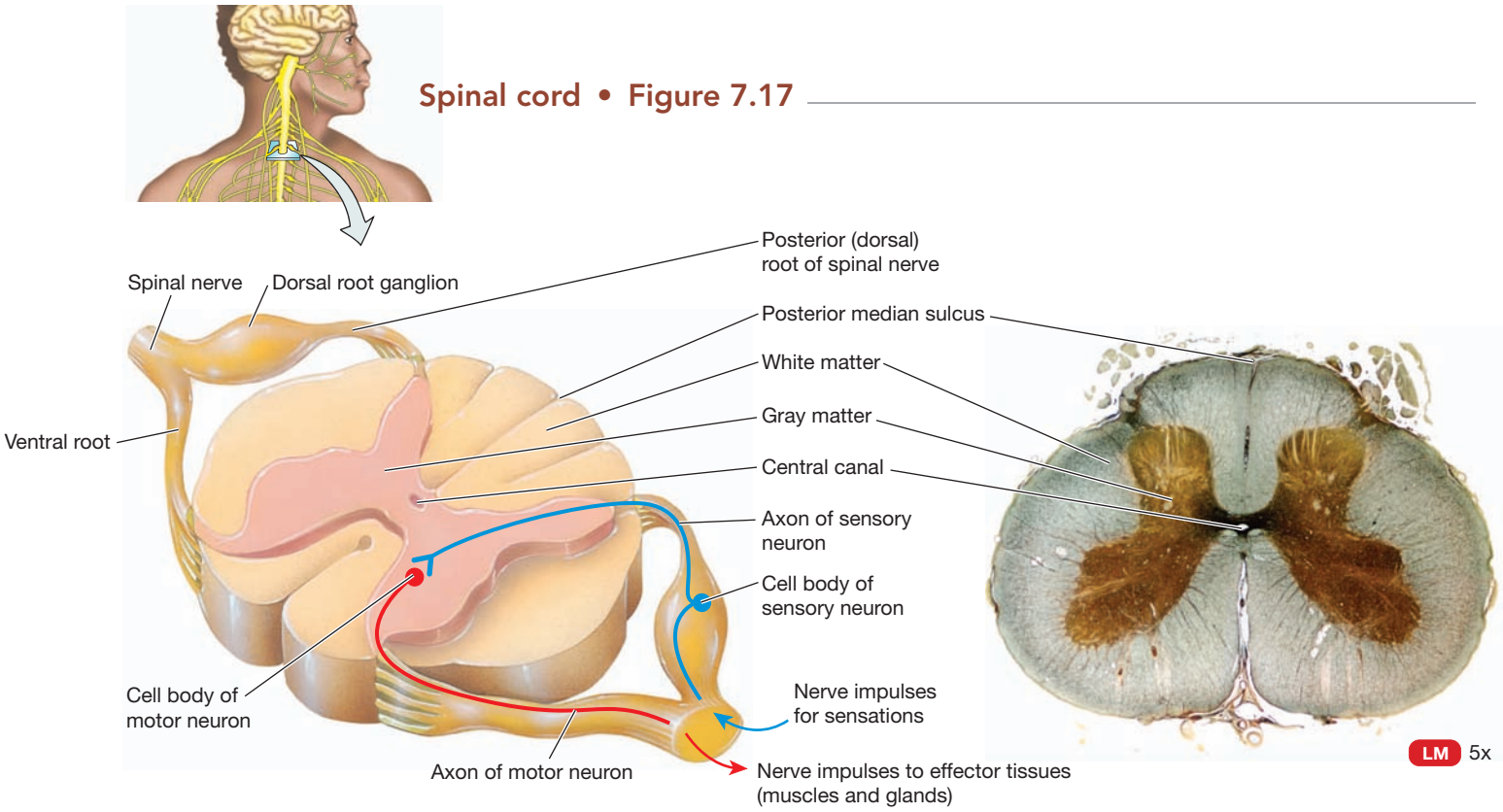
The Spinal Cord Connects to Almost Everywhere

The spinal cord, which extends from the brain into the vertebral column, is the second organ of the CNS and is shown in Figure 7.17. The spinal cord consists of white tracts surrounding gray matter (the opposite of the arrangement in the brain). Thus, the exterior of the spinal cord is composed of communication tracts running up and down the spinal cord, while the interior is composed of connections between spinal nerves. The spinal cord is the main route of communication between the brain and the body. Sensory information enters the spinal cord via the **dorsal root** and is transferred to an upward tract heading toward the brain.

Motor impulses generated in the brain are passed through the downward tracts of the spinal cord to the nerves of the body. These tracts are often called pyramids. The pyramids are continuations of the tracts in the medulla oblongata that cross to carry information generated in one hemisphere over to the opposite side of the body.

Sensory information that demands immediate attention may initiate a **reflex**. Reflexes are extremely quick responses to sensory stimuli, running through the spinal cord from the dorsal root immediately to the ventral root and bypassing the brain. Evolution honed this brilliant system to keep our vertebrate ancestors safe from danger. Incoming sensory information is transferred to an association neuron in the innermost portion of the spinal cord and then directly to a motor neuron. The motor neuron transmits an immediate response through the ventral root to the effector organ.

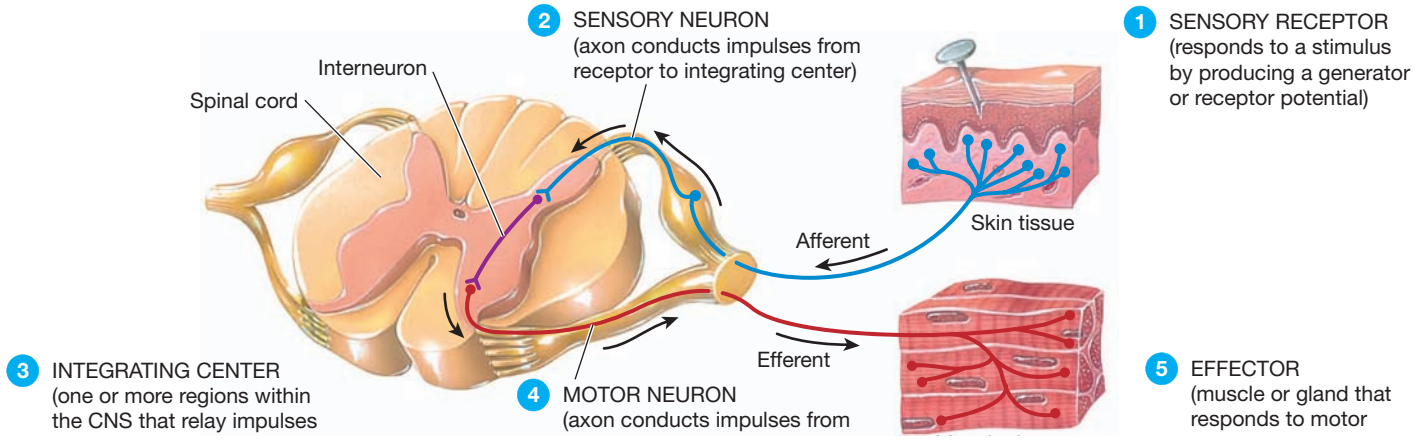
Spinal cord • Figure 7.17



a. Transverse section of thoracic spinal cord

b. Transverse section of thoracic spinal cord

Reflex arc • Figure 7.18



Reflexes generate an immediate, life-saving motor response. You pull your hand from an open flame even before you consciously recognize the heat. As you pull your hand away, the "that's hot!" information is still traveling to your brain. There, a series of motor responses begins, causing you to rub your hand, inspect it for burns, and exclaim in surprise or pain. Fortunately, before all these brain-initiated motor responses can occur, the reflex has already removed your hand from danger (see Figure 7.18).

CONCEPT CHECK

STOP

1. **What** are the coverings of the brain? **What** structures do they protect?
2. **What** are the functions of the various parts of the brain?
3. **How** does the anatomy of the spinal cord differ from the anatomy of the brain?
4. **What** are the steps in a typical reflex?

7.4 The Peripheral Nervous System Extends the Central Nervous System

LEARNING OBJECTIVES

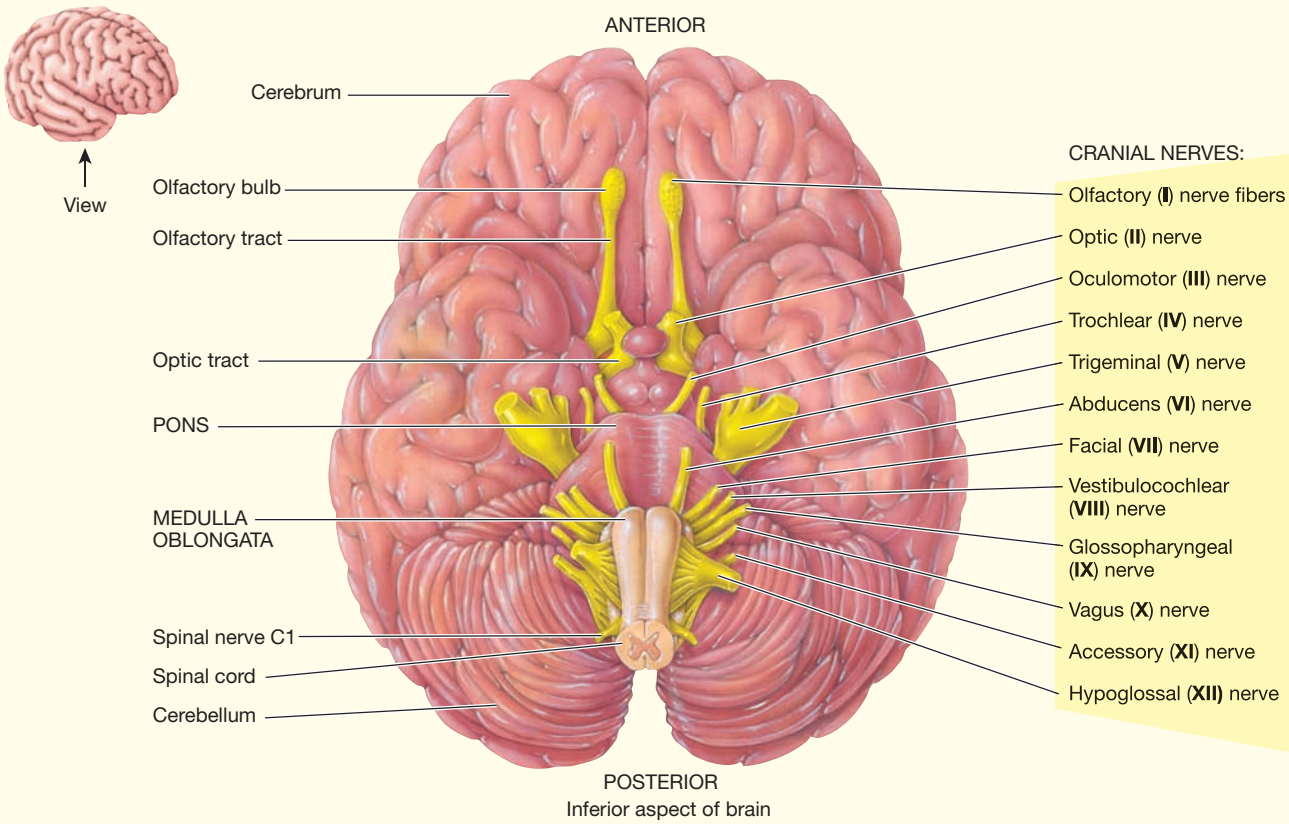
1. **Describe** the difference between spinal and cranial nerves.
2. **Compare** the sympathetic and parasympathetic aspects of the PNS.

The peripheral nervous system (PNS) is composed of all neural tissue other than the brain and spinal cord. The PNS includes the nerves that protrude from these structures. The 12 nerves that extend from the brain are called the **cranial nerves**. These nerves are identified by name and a Roman numeral, as shown in Figure 7.19. Some are sensory only, others are motor only, and the remainder serve both functions. Most cranial nerves carry impulses that deal with the head, neck, and facial regions. However, the **vagus nerve** (X) branches to the throat, voice box, and abdominal organs.

Thirty-one pairs of **spinal nerves** extend from the spinal cord. These are all mixed nerves, carrying both sensory and motor information. Each spinal nerve connects with body structures near the region where it originates, as in Figure 7.20.

Sensory neurons carry information to the CNS. They join other motor and sensory neural processes to form a spinal nerve. These sensory neurons separate from the motor neurons before they enter the spinal cord. Sensory neurons enter the spinal cord at the back, through the dorsal root of the spinal nerve. Their cell bodies are located just outside the CNS, in the dorsal root ganglia. Motor

Brain and cranial nerves • Figure 7.19



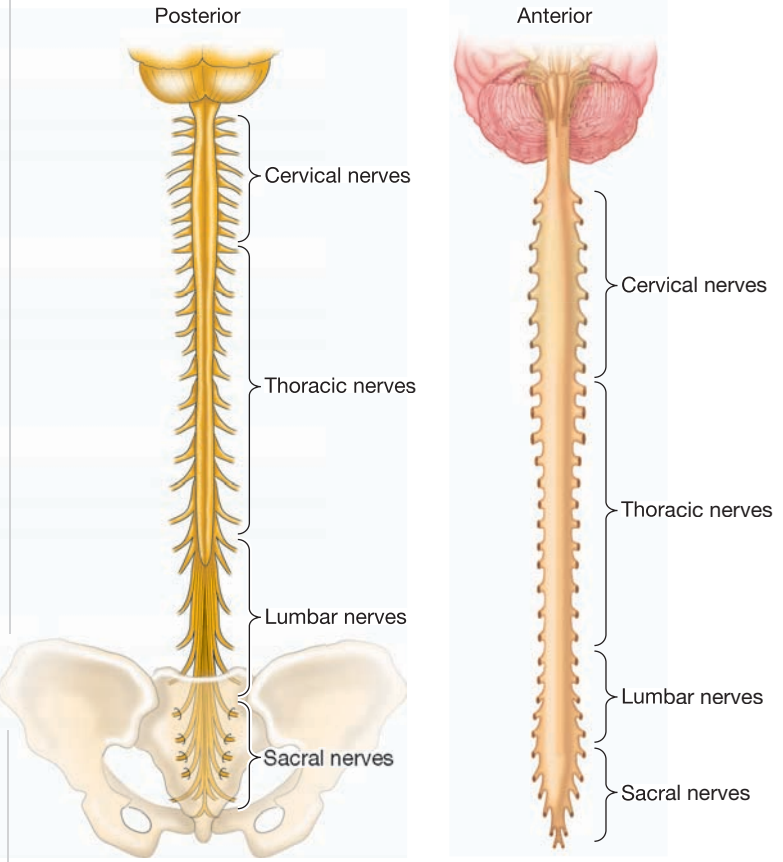
neurons exit the spinal cord at the front. Their cell bodies are within the CNS, and their axons extend out through the ventral root of the spinal cord. These motor and sensory neural processes can be long—the axon of the motor neuron that moves the great toe reaches from the sacral area of the spinal cord down the entire length of the leg, a distance of up to 1 meter!

The PNS Also Contains Sympathetic and Parasympathetic Nerves

Autonomic nerves—the ones you do not consciously control—are also part of the PNS. Along with the physiological differences in sympathetic and parasympathetic divisions discussed previously, these nerves display anatomical differences (see **Figure 7.21** on the next page). The sympathetic nervous system includes nerves in the thoracic and lumbar region of the spinal cord only. Sympathetic fibers extend from the spinal cord to a series of **ganglia** (group of cell bodies in PNS) called the **sympathetic chain**, on either side of the spinal cord. At these ganglia, neurons from the CNS synapse with a second neuron that extends to the effector organ. Thus, sympathetic neurons leaving the spinal cord are shorter than those leaving the sympathetic chain. We call the neurons leaving the spinal cord and synapsing in the ganglia preganglionic. Those that leave the ganglion and synapse with the effector organ are called postganglionic.

Parasympathetic fibers are found only in the cranial and sacral regions of the spinal cord. These neurons leave the spinal or cranial nerve and join a ganglion near or in the effector organ. The parasympathetic preganglionic fibers are long, and the postganglionic neurons are extremely short.

Spinal nerves • Figure 7.20

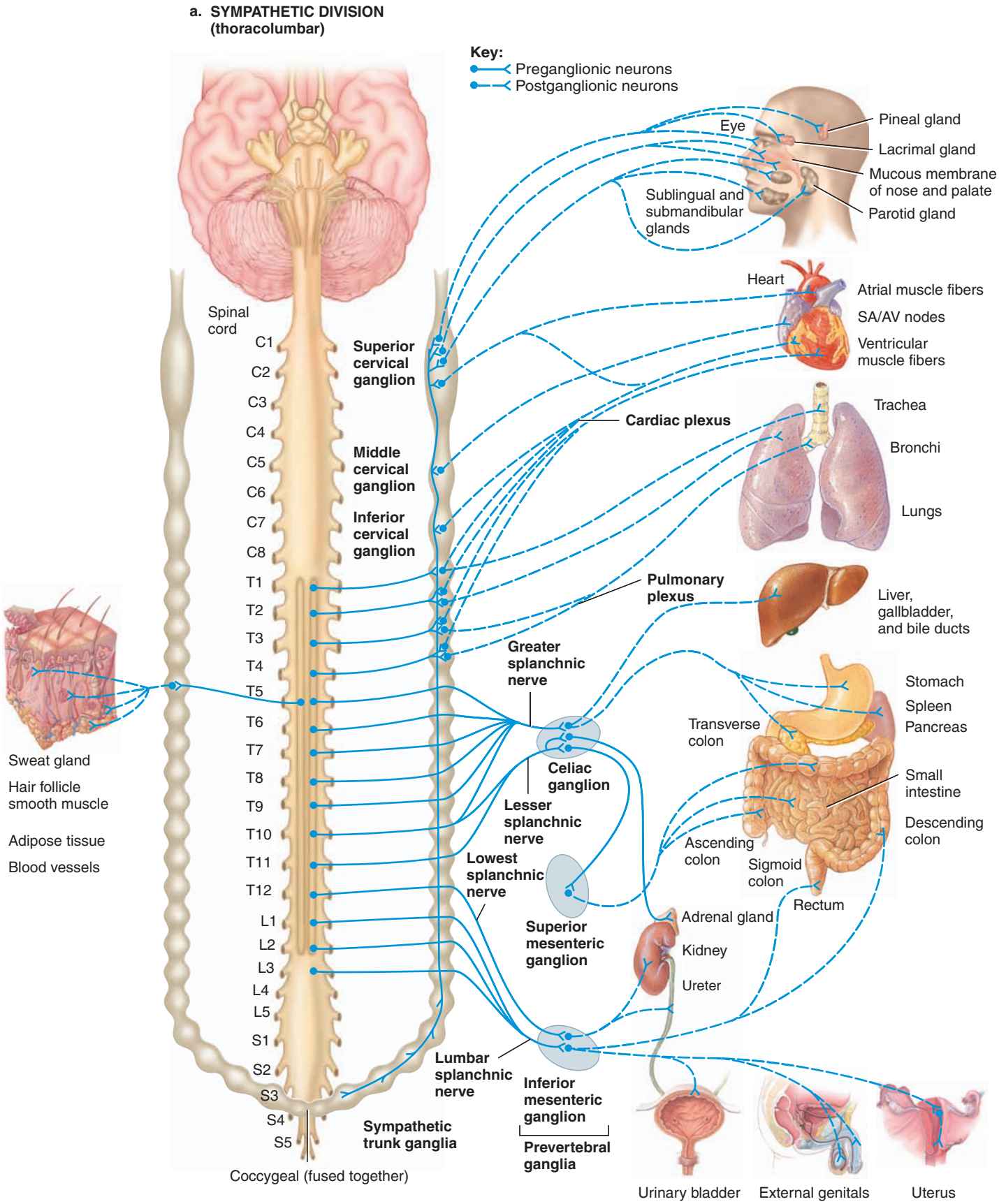


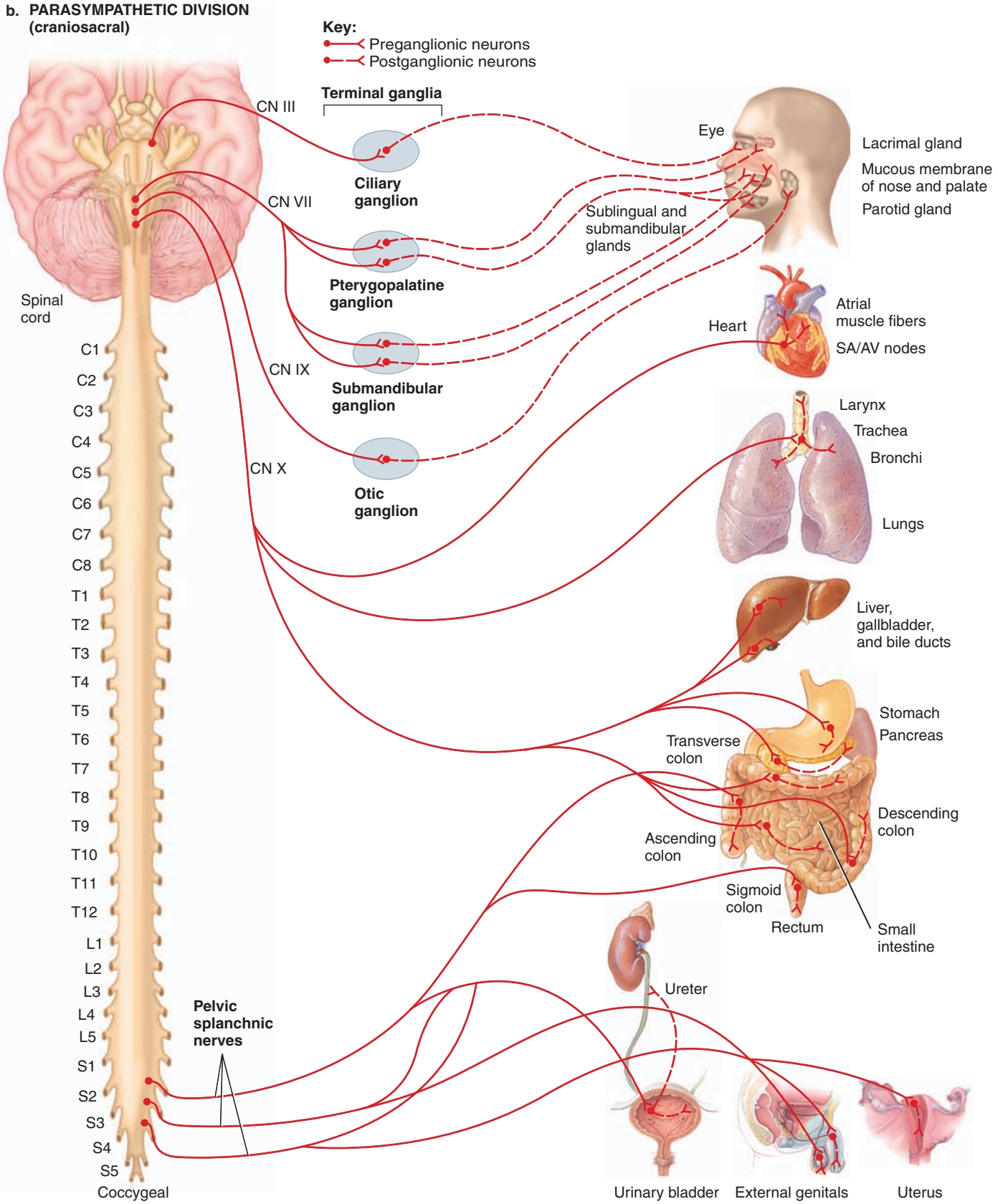
Nerve	Type	Function
I	Sensory	Smell
II	Sensory	Vision
III	Mixed	Sensory: proprioception Motor: movement of eyelid and eyeball; accommodation of lens
IV	Motor	Movement of eyeball
V	Mixed	Sensory: touch, pain, temperature, proprioception Motor: chewing
VI	Mixed	Sensory: proprioception Motor: movement of eyeball
VII	Mixed	Sensory: taste, proprioception Motor: facial expressions, secretion of tears and saliva
VIII	Mixed	Sensory: equilibrium and hearing Motor: sensitivity of receptors in ear
IX	Mixed	Sensory: taste, touch, pain on tongue; O_2, CO_2; and blood pressure levels Motor: swallow, speech
X	Mixed	Sensory: taste and pharynx sensations Motor: swallow, cough, speech, GI movements
XI	Mixed	Sensory: proprioception Motor: swallow, head and shoulder movements
XII	Mixed	Sensory: proprioception Motor: tongue movement

CONCEPT CHECK STOP

1. **What** is the difference between spinal and cranial nerves?
2. **How** do sympathetic neurons differ anatomically from parasympathetic neurons?

Sympathetic and parasympathetic nerve fibers • Figure 7.21




b. PARASYMPATHETIC DIVISION
(craniosacral)
Key:
Preganglionic neurons
Postganglionic neurons
Terminal ganglia
CN III
CN VII
CN IX
CN X
Ciliary ganglion
Pterygopalatine ganglion
Submandibular ganglion
Otic ganglion
Spinal cord
C1
C2
C3
C4
C5
C6
C7
C8
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
T11
T12
L1
L2
L3
L4
L5
S1
S2
S3
S4
S5
Coccygeal
Pelvic splanchnic nerves
Eye
Lacrimal gland
Mucous membrane of nose and palate
Parotid gland
Sublingual and submandibular glands
Heart
Atrial muscle fibers
SA/AV nodes
Larynx
Trachea
Bronchi
Lungs
Liver, gallbladder, and bile ducts
Stomach
Pancreas
Transverse colon
Descending colon
Ascending colon
Sigmoid colon
Rectum
Small intestine
Ureter
Urinary bladder
External genitals
Uterus

Summary

THE PLANNER

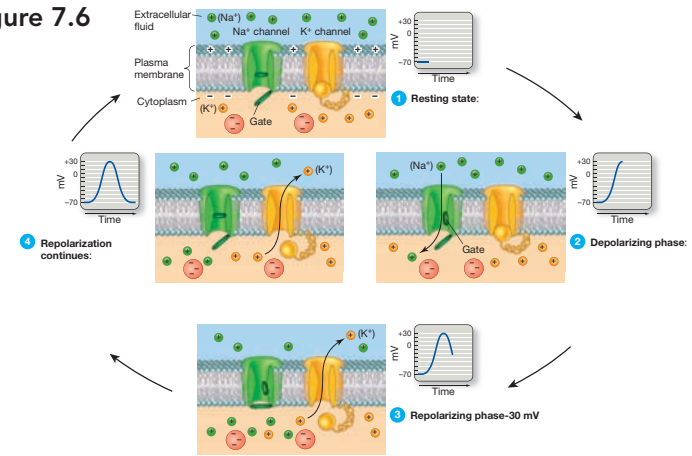
1 The Nervous System Is Categorized by Structure and Function 156

- The nervous system is responsible for maintaining homeostasis by reacting almost instantaneously to stimuli. It works in concert with the endocrine system to maintain homeostasis. The work of the system is performed by **neurons**, supported by neuroglial cells.
- The nervous system is divided into the **central** and **peripheral nervous systems**. The CNS includes the brain and spinal cord and is the main integration center of the body. The PNS includes the autonomic, sensory, and somatic nerves of the body. The autonomic division is further subdivided into the sympathetic and parasympathetic divisions. A nerve consists of a bundle of neurons, protected by layers of connective tissue. Sensory information enters the CNS, which analyzes it and sends a motor response through the PNS to muscular or glandular tissue.
- The nervous system contains neurons and neuroglial cells. Neurons carry impulses, whereas glial cells carry out supporting functions. Sensory neurons detect conditions in the environment or body, motor neurons carry instructions to the body, and interneurons connect the two systems. Dendrites bring signals to the cell body, and the long axons deliver signals to other neurons or tissue.

2 Neurons Work Through Action Potentials 160

- An action potential, shown here, is a brief change in electrical conditions at a neuron's membrane that occurs when a neuron "fires." An action potential occurs when the charge differential across the neuron's membrane suddenly reverses polarity, as a result of changing ion concentrations inside and outside the neuron. Impulse speed is determined by axon diameter, degree of myelination, and other factors.

Figure 7.6

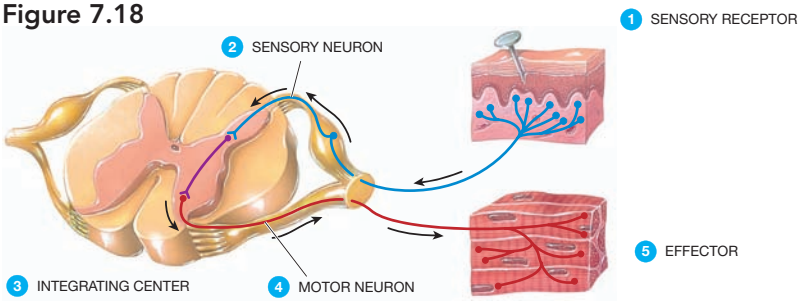


- **Neurotransmitters** carry signals from one neuron to the next across a tiny gap called the synapse. Inhibitory postsynaptic potentials (IPSPs) and excitatory postsynaptic potentials (EPSPs) also influence the generation of action potentials.

3 The Brain and Spinal Cord Are Central to the Nervous System 167

- The spinal cord carries impulses to and from the brain. The CNS organs are nourished and protected from physical damage by cerebrospinal fluid (CSF) and **meninges**. The lobes and internal structures of the brain each have distinct, but overlapping, functions.
- The brain stem contains vital centers that regulate heart rate, breathing, and blood pressure.
- The cerebellum focuses on muscles and movement.
- The diencephalon is a relay center between other parts of the brain, whereas the cerebrum is a central processing center, home of logic and skills.
- The reticular activating system is the brain's alarm clock. Reflexes are two- or three-neuron circuits that bypass the brain to allow fast retreat from injury, as seen in this illustration.

Figure 7.18



4 The Peripheral Nervous System Extends the Central Nervous System 180

- The peripheral nervous system includes the nerves that protrude from the brain and spinal cord. The PNS originates with 12 cranial nerves and 31 pairs of spinal nerves. Peripheral nerves may be sensory, motor, or mixed.
- The autonomic nerves are not under conscious control. Sympathetic autonomic nerves control visceral organs from the thoracic and lumbar regions of the spinal cord. Parasympathetic autonomic nerve fibers emerge from the cranial and sacral regions of the spinal cord.

Key Terms

- afferent 157
- autonomic division (ANS) 158
- cerebrospinal fluid (CSF) 168
- cortex 176
- efferent 157
- gyri (gyrus) 176
- hemispheric lateralization 177
- medulla oblongata 170
- membrane potential 160
- myelin 163
- neuron 157
- neuroglia 158
- neurotransmitter 157
- nuclei 177
- pons 170
- postsynaptic neuron 164
- presynaptic neuron 164
- proprioception 157
- somatic division 158
- special senses 177
- sulci (sulcus) 176
- terminal bulb 164
- tracts 170

Critical and Creative Thinking Questions

1. Compare the structure of a nerve to the structure of a muscle. What explains the anatomical similarities? What are the main differences?
2. Review the steps in an action potential, as well as the definition of IPSP and EPSP. Using what you know, describe a neuron that is exhibiting an IPSP. How would the ion concentrations across the membrane be different from those in an EPSP? Can you predict what ion conditions would cause an EPSP?
3. Why are reflexes faster than conscious thought? Why is the response slower when the brain is involved? Why do we even have reflexes?
4. **CLINICAL CLICK QUESTION**
   Kalee was looking forward to her years as a grandmother. Taking care of her grandsons and working in her garden sounded wonderful. As she neared her 58th birthday however, Kalee noticed that her hands were shaking when she was working with her plants. She also noted that she was slower than she used to be, and often her body felt stiff. Kalee passed these off as symptoms of increasing age until she began to have difficulty maintaining her balance. Concerned, she visited her doctor. After a series of inconclusive tests, including blood work and physical exams, her doctor suggested that she see a neurologist. What does he suspect Kalee is suffering from? See http://www.parkinson.org/Page.aspx?pid=225 for more information.

   The neurologist noted that Kalee's speech was muffled, and she shuffled as she walked. Approximately 1 million people in the United States suffer from similar symptoms, leading him to believe that Kalee's brain is not producing enough dopamine. He prescribed a dopamine agonist to help increase her levels of dopamine. With this drug, Kalee's tremors subsided and her gait became more fluid once again. What type of neurotransmitter is dopamine? Why might Kalee need to supplement her production of dopamine? To answer these questions, visit http://health.yahoo.com/nervous-medications/dopamine-agonists-for-parkinson-s-disease/healthwise--hw91583.html.

What is happening in this picture?

The eyes are bringing the image to the visual cortex of the brain, and the brain is interpreting the scene—identifying colors and shapes. This comes from the association areas and long-term memory retrieval. The motor cortex is sending impulses to the hand and fingers to recreate that scene on paper. All of this is being carried out by action potentials in the brain, spinal cord, and peripheral nerves.

Think Critically

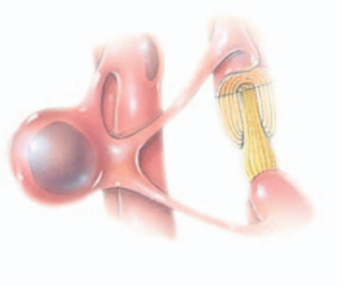
1. What is the limbic system adding to the artist's reaction to the scene?
2. Do you agree with the statement that the artist's painting is a result of miniscule changes in local concentrations of sodium and potassium ions? Why or why not?

Self-Test

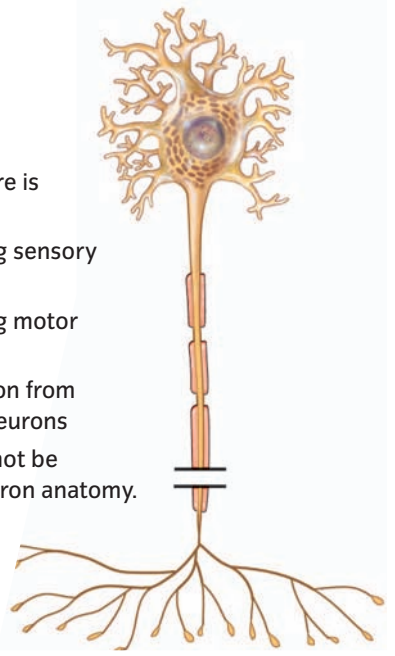
1. The functional unit of the nervous system is _____.
   a. the brain
   b. the brain and spinal cord
   c. the neuron
   d. the neuroglia

2. Information reaches the CNS from the _____.
   a. afferent division of the PNS
   b. efferent division of the PNS
   c. motor neurons
   d. sympathetic division

3. The type of neuroglion shown is a(n) _____.
   a. astrocyte
   b. motor neuron
   c. microglion
   d. oligodendrocyte

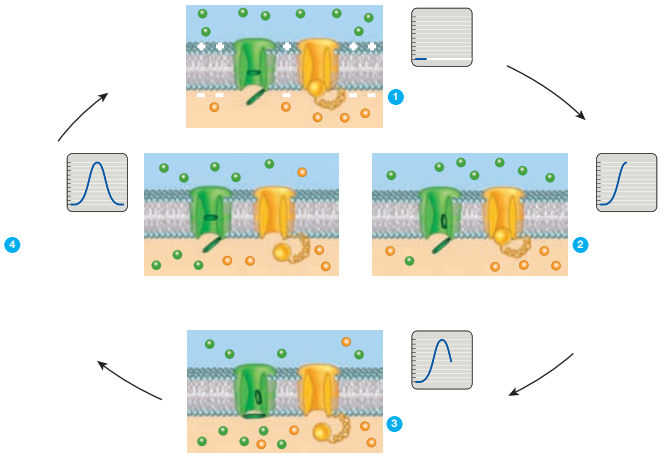


4. The neuron pictured here is responsible for _____.
   a. sending and receiving sensory information
   b. sending and receiving motor information
   c. integrating information from sensory and motor neurons
   d. Neuron function cannot be determined from neuron anatomy.



5. The type of membrane protein that allows ions to enter the cell only during a shift in membrane voltage is a _____.
   a. mechanically regulated channel
   b. ligand-gated channel
   c. voltage-gated channel
   d. leaky gated channel

Questions 6–8 refer to the image below.

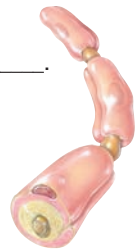


6. The original membrane potential of a resting neuron is _____.
   a. –70 mV
   b. +190 mV
   c. 0 mV
   d. dependent on neuron location

7. The first ion to enter the neuron at the beginning of an action potential is _____.
   a. calcium
   b. potassium
   c. sodium
   d. ATP

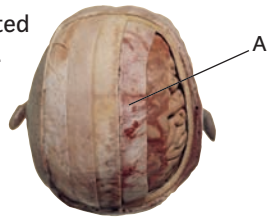
8. The period of time immediately after an action potential, during which the neuron cannot send a second action potential, is the _____.
   a. relative refractory period
   b. absolute refractory period
   c. dead zone
   d. sodium/potassium ATPase period

9. The function of the cell shown in the diagram is to _____.



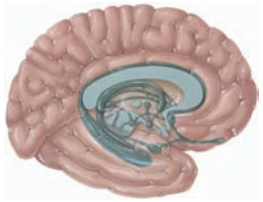
   a. myelinate PNS neurons
   b. myelinate CNS neurons
   c. increase action potential propagation speed
   d. decrease action potential propagation speed
   e. Both a and c are correct.

10. The specific layer of the meninges indicated by the letter A on the figure is the _____.



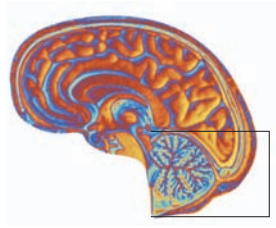
   a. dura mater
   b. pia mater
   c. arachnoid

11. The portion of the brain indicated in teal green in this figure is the _____.



   a. limbic system
   b. cerebrum
   c. cerebellum
   d. diencephalon

12. The functions of the structure shown include _____.

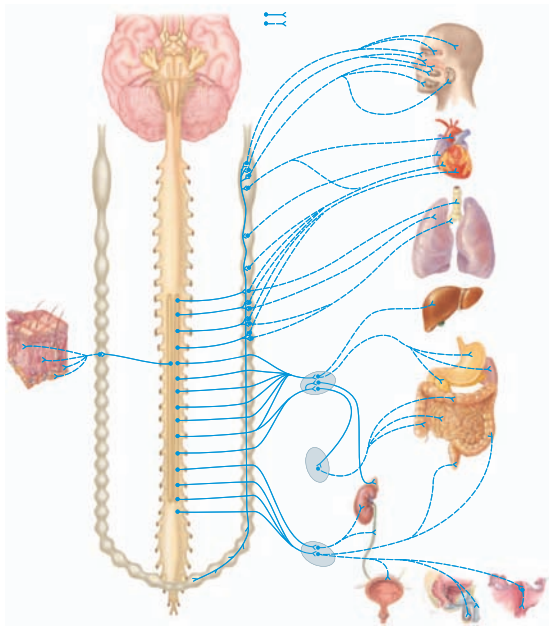


   a. sensory interpretation
   b. proprioception
   c. learning
   d. heart rate control

13. The portion of the brain that is responsible for emotions is the _____.
   a. hypothalamus
   b. thalamus
   c. reticular formation
   d. limbic system

14. The surface of the spinal cord is white, indicating that it functions as _____.
   a. a highway for information traveling up and down the cord
   b. an integration center, where impulses are connected to one another and then passed to the brain
   c. an insulation layer surrounding the functioning neurons underneath
   d. In nerve tissue, color does not indicate function.

15. The function of the autonomic division of the PNS shown in the figure is _____.
   a. increased digestive activity
   b. increased respiratory and heart rate
   c. increased urinary output
   d. decreased mental alertness



THE PLANNER

Review your Chapter Planner on the chapter opener and check off your completed work.

8 The Special Senses

Roller coasters and tilt-a-whirls are notorious for inducing nausea, but some people get similar symptoms from the little swerves and dips of a journey by car, boat, or plane. These folks break into a cold sweat and get a headache. They get nauseous and feel listless or uneasy.

The syndrome goes by many names: carsickness, seasickness, airsickness, or, more generically, motion sickness. Many people suffer from it, at least under some conditions—even 70% of first-time astronauts.

The problem seems to arise from a war between the senses. When you sit in the back seat of a car, most of what you see is stationary in relation to you, so your eyes tell your brain that you are not moving. However, other senses say you are moving. The seat presses against your skin on each bump, your joints flex, and your inner ear registers changes in direction. As your brain struggles with what to believe, the conflicting messages cause inner turmoil, the release of stress hormones, and misery.

The special senses evolved to protect organisms from danger as they move through their environment, so they can reach reproductive age—anything that affects reproduction can have species-wide effects. As motion sickness shows, the special senses can be fooled and delude us into believing we face danger, and can even render us totally incapacitated in certain circumstances. Obviously, these senses can affect us whether we want them to or not.

CHAPTER OUTLINE

The Special Senses Tell Us About Our Environment 190

- Smelling and Tasting Are Chemical Senses
- Hearing Involves Membranes, Bones, Waves, and Hairs
- Equilibrium Is Also Housed in the Inner Ear

Vision Is Our Most Acute Sense 196

- The Eye Has Three Layers
- The Lens Changes Shape to Achieve Optimal Optics
- Photoreceptors Detect Light in the Retina
- Visual Nerve Impulses Travel to the Brain

The Special Senses Are Our Connection to the Outside World 203

- Like Vision, Hearing Can Diminish with Age

CHAPTER PLANNER

- ❑ Study the picture and read the opening story.
- ❑ Scan the Learning Objectives in each section: p. 190 ❑ p.196 ❑ p. 203 ❑
- ❑ Read the text and study all figures and visuals. Answer any questions.

Analyze key features

- ❑ I Wonder..., p. 190
- ❑ Biological InSight, p. 193
- ❑ Process Diagram, p. 202
- ❑ Health, Wellness, and Disease, p. 204
- ❑ What a Scientist Sees, p. 205
- ❑ Ethics and Issues, p. 206
- ❑ Stop: Answer the Concept Checks before you go on: p. 196 ❑ p. 203 ❑ p. 206 ❑

End of chapter

- ❑ Review the Summary and Key Terms.
- ❑ Answer the Critical and Creative Thinking Questions.
- ❑ Answer What is happening in this picture?
- ❑ Answer the Self-Test Questions.

8.1 The Special Senses Tell Us About Our Environment

LEARNING OBJECTIVES

1. **Describe** the special senses.
2. **Explain** the physiology of the chemical senses of taste and smell.
3. **Relate** the structure of the outer, middle, and inner ear to the functions of each.
4. **Discuss** the physiology of balance and hearing.

The intricate functioning of the nervous system is best appreciated when discussing our senses. Human biologists often distinguish between "somatic" or "whole body" senses and the special senses. Somatic senses involve receptors from more than one place in the body, and may help coordinate muscle movement and maintain body temperature. These senses are treated in several places throughout this book. The special senses, on the other hand, are extremely sensitive receptors that supply us with detailed information about the world around us, including the sights, sounds, smells, and tastes present in our surroundings. The wealth of information they provide occupies most of our brain and forms the basis for our logical and rational decisions.

We rely on our senses to get us through even the simplest task. To eat an apple, we first locate it visually, and we may scan it for rotten spots or an appealing color. Picking it up, we gain more information from the firmness of the skin and the fruit's density. We may even raise the apple to our nose and smell it before taking the first bite. Consciously or not, we assess that first bite to make sure it tastes right. Each of these small, practically automatic actions supplies information to the brain through the special senses.

WILEY PLUS Video

I WONDER...

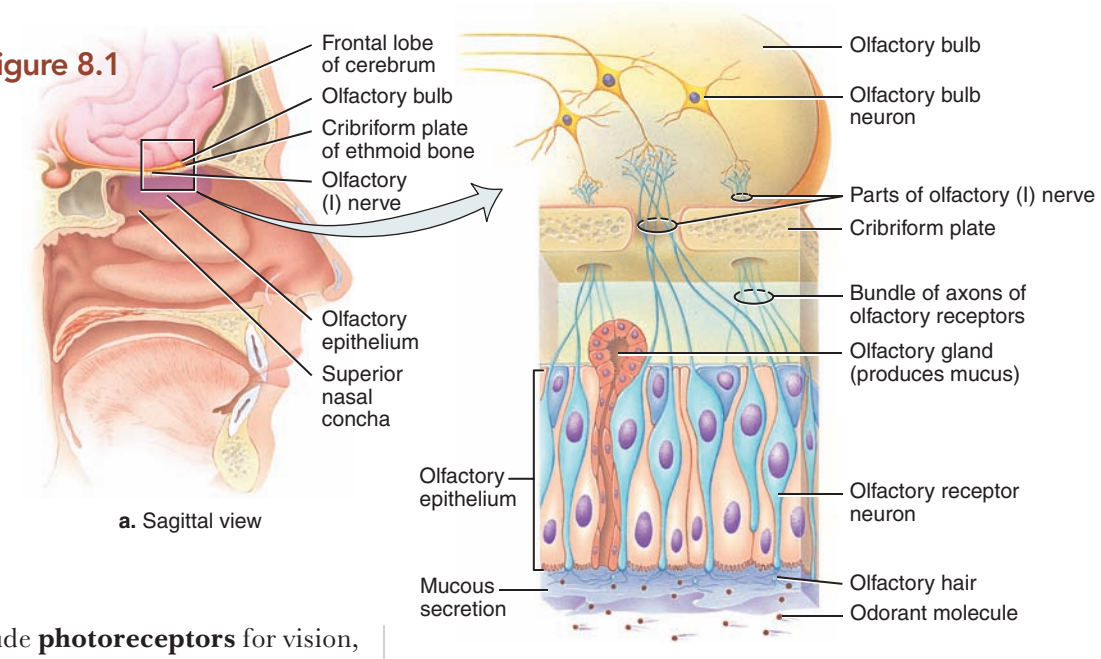
NATIONAL GEOGRAPHIC

What Is the Role of Odor in Human Attractiveness?

Animals use chemicals to communicate many kinds of information, and not surprisingly it turns out that humans do likewise. Human chemical communication is similar in some ways to other animals' use of chemicals to identify individuals, mark social rank and territories, and signal reproductive status. In animals, many of these behavior-affecting chemicals are released as airborne compounds called *pheromones*. Moths, for example, release vanishingly small concentrations of pheromones to attract mates. Honeybees use pheromones when sharing information, such as the route to food sources, with the rest of the hive. Many vertebrates use pheromones to signal readiness for mating.

Do humans also respond to pheromones? Some perfume makers are eager to market the idea that pheromones can facilitate dating and mating, but the claim is still debatable. For years, scientists denied that humans could respond to pheromones because we do not have a vomeronasal organ, the anatomical structure in the nasal passages that other vertebrates use to detect pheromones. Now it appears that we do have such an organ, although it may deteriorate after birth. The exact role of pheromones and the vomeronasal organ in humans is uncertain. However, amid a cascade of bizarre discoveries about how people communicate with chemicals, additional olfactory surprises would not be too astonishing.

Olfactory anatomy • Figure 8.1



a. Sagittal view

b. Enlarged aspect of olfactory receptors

Our special senses include **photoreceptors** for vision, **mechanoreceptors** for hearing and balance, and **chemoreceptors** for smell and taste. (There is an in-depth discussion of mechanoreceptors in the skin in Chapter 9.) We are extremely visual creatures, using our eyes to provide most of our clues about the environment. Hearing is our second most acute sense, providing enough information to allow us to move through the environment even when we cannot see. Our sense of balance, or equilibrium, is closely allied with hearing in that both reside in the ear. However, balance is often overruled by our strong visual perceptions. The thrill of amusement park rides and the awful feeling of motion sickness both come from our brain trying to reconcile visual information with conflicting balance information from the inner ear. The senses of smell and taste are interwoven to provide us with a subtle palate for food and an ability to detect a wide range of aromas.

Although we rely heavily on these senses, they do not always supply us with accurate information. It is true that a stronger stimulus, such as increasing the volume on the radio, activates more receptors, and sends more impulses from the receptors to the brain. However, we also can experience **sensory adaptation**, which occurs when we get used to an unchanging smell, sight, or taste. The perception of that sense simply decreases to the point where we are not aware of it any longer. How many times have you enjoyed the smell of your morning perfume or aftershave, only to think that it has "worn off" during the day? In truth, it hasn't worn off, but rather your sense of smell has adapted, and you do not perceive the scent again until you increase the stimulus by splashing on a dab more. Scientists are still researching whether the receptors stop sending impulses during sensory adaptation or whether the brain stem's reticular activating system filters them out. See *I Wonder… What Is the Role of Odor in Human Attractiveness?* for another look at the role smell may play in our lives.

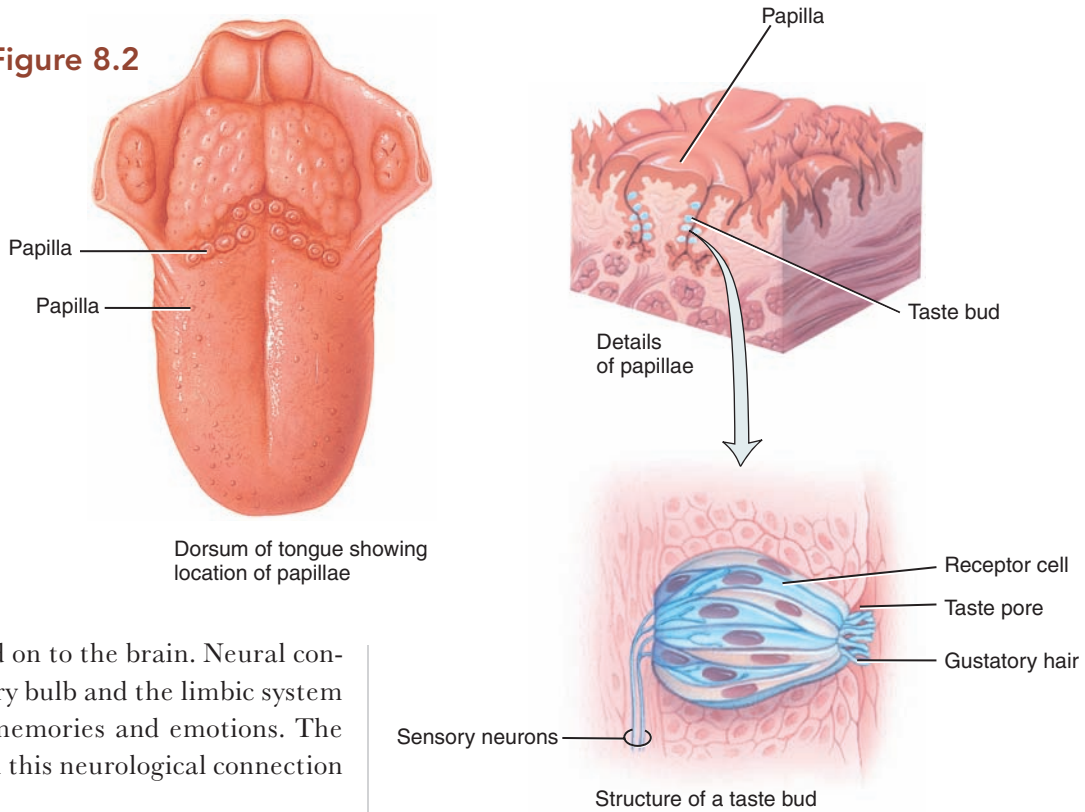
Smelling and Tasting Are Chemical Senses

olfaction The sense of smell.

gustation The sense of taste.

Both **olfaction** and **gustation** are chemical senses, because these sensory receptors respond to chemicals dissolved in the mucus lying over them. Olfaction occurs in the upper chambers of the nasal passages, on the roof of the nasal cavity. When we smell something, we take deep breaths to flood the upper portion of the nasal cavity with inhaled odor. See **Figure 8.1**. Olfactory cells extend from the **olfactory bulb** (at the end of cranial nerve I) through the cribriform plate and into the mucus lining of the nasal cavity. The sensory receptors themselves are a small yellow patch of olfactory epithelium in the lining of the nasal cavity. In the olfactory epithelium there are neural stem cells that give rise to new olfactory neurons approximately every 40 days. These stem cells are of great interest to neuroscientists, as they are one of only a few sites where neurons are formed in adults. Each olfactory cell is a modified neuron that ends in approximately six to twelve olfactory cilia, which bear at least one of many thousands of specific olfactory receptors. When the receptor binds its specific odor molecule, a sensory impulse is

Taste bud anatomy • Figure 8.2



sent to the olfactory bulb and on to the brain. Neural connections between the olfactory bulb and the limbic system explain why smells trigger memories and emotions. The perfume industry depends on this neurological connection between odor and emotion.

The sense of taste is closely allied with olfaction. Have you noticed how food loses its appeal when you suffer nasal congestion? That is because much of our sense of taste derives from our sense of smell. In the mouth, food is chemically degraded by enzymes in saliva. The receptors for taste are in roughly 10,000 taste buds, most of which are on the tongue, in small bumps called **papillae** (singular: *papilla*). Taste buds can distinguish only four or five categories of taste: sweet, sour, salty, bitter, and the recently reported umami, which is described as "savory" and "meaty." Like the olfactory epithelium, individual taste buds respond to only one class of chemical compound. Taste buds collectively respond to only four or five classes of compounds rather than the thousands that olfactory neurons recognize. Individually, taste buds respond to at least two, and often more, taste qualities. When stimulated, taste bud receptor cells send information on to the brain where the overall taste of the food we are eating is determined. All of this is shown in Figure 8.2.

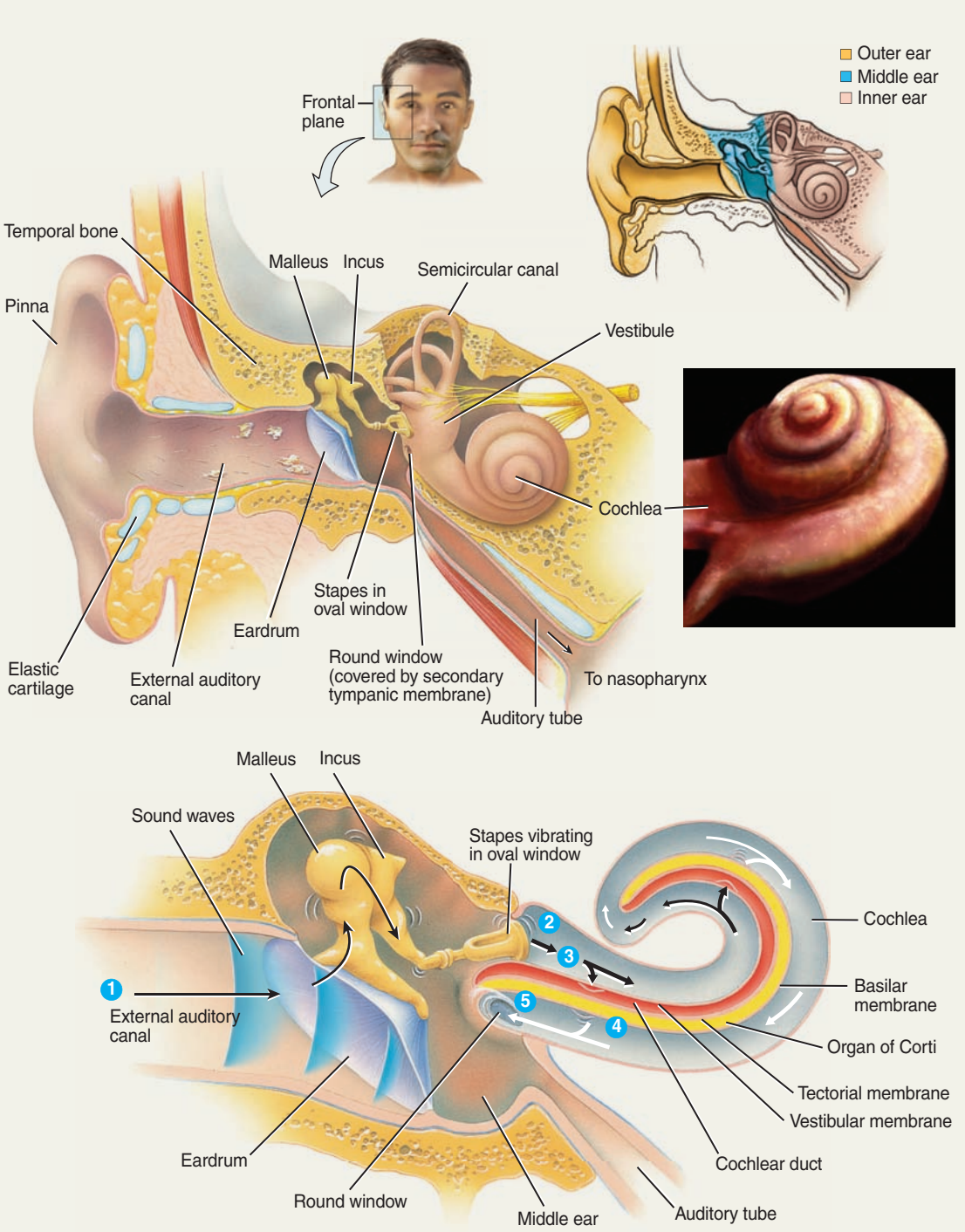
We rarely classify a food as tasting simply sweet or bitter. We describe coffee as "rich" or "full-bodied." One major caffeine purveyor even describes its flavors as "elegant sweet fruit" and "intense floral notes." The subtle differences in food tastes are actually due to the involvement of olfaction. Food in the mouth is dissolved in the mucus as we chew. At the back of the oral cavity, posterior to the **uvula**, lies a hole connecting to the nasal cavity. During swallowing, the uvula closes this hole, preventing swallowed items from being propelled out the nose. When the hole is open, food in the mouth can be smelled by the olfactory epithelium. The combination of the food's texture (determined by the tongue), taste (sweet, sour, salty, bitter, or umami), and odor (determined by the olfactory epithelium) are all related to our description of the flavor of a food.

uvula The tab of soft tissue that hangs down in the back of the throat, visible as a pointed tab.

Hearing Involves Membranes, Bones, Waves, and Hairs

Our sense of hearing gives us the ability to detect the slightest noises. The movie *Ray* documented the life story of rhythm-and-blues legend Ray Charles. Born with full vision, Ray lost his sight in grade school. Few of us use our ears as well as Ray Charles did, even though we were born with the same capability. In a touching scene, 10-year-old Ray learned he could "see" by listening carefully. By following the sound of a cricket's feet on the wood floor, he located and caught the cricket. He turned to his mother and asked her why she was crying as she watched him discover his world through sound instead of sight.

The ear, as we all know, houses our sense of hearing, as shown in Figure 8.3. The ear has three functional parts: the **outer**, **middle**, and **inner** ear. The outer ear is composed of



1. When the tympanic membrane vibrates in response to sound waves, the auditory ossicles move, pulling the stapes in and out where it is connected to the oval window. This pulling and pushing creates fluid waves within the inner ear.
2. As the pressure waves pass through the cochlea, they transfer their energy to the structures of the cochlea. When these waves create enough energy, they deform the cochlear canal.
3. The tectorial membrane inside the organ of Corti is deformed.
4. The supporting stereocilia bend.
5. The bending stimulates the generation of a nerve impulse, sending information on the pitch and intensity of the sound to the brain (not pictured in the figure).

the **pinna** and external **auditory canal**, both of which capture sound waves and funnel them to the middle ear.

The ear drum, or **tympanic membrane**, marks the beginning of the middle ear. Compression waves in the air (sound) cause the membrane to vibrate, converting sound into mechanical motion. Attached to the inside of the tympanic membrane is the **malleus**, one of the three smallest bones in the human body. The vibrating tympanic membrane moves the malleus, which in turn moves the **incus** through a synovial joint. One more small bone, the **stapes**, is joined to this chain through another tiny synovial joint. The stapes is the final small bone, or ossicle, of the middle ear.

These three bones can dampen or amplify the movement of the tympanic membrane. Extremely loud noises that cause tremendous vibration of the tympanic membrane are dampened in the middle ear when tiny skeletal muscles tighten at these synovial joints. We can hear soft noises more clearly as these muscles relax, allowing the bones to move freely.

Beyond the stapes is the inner ear. The **stapes** connects to the **oval window**, a membrane that functions like the tympanic membrane. The oval window bounces in response to movement of the stapes, creating fluid waves in the inner ear.

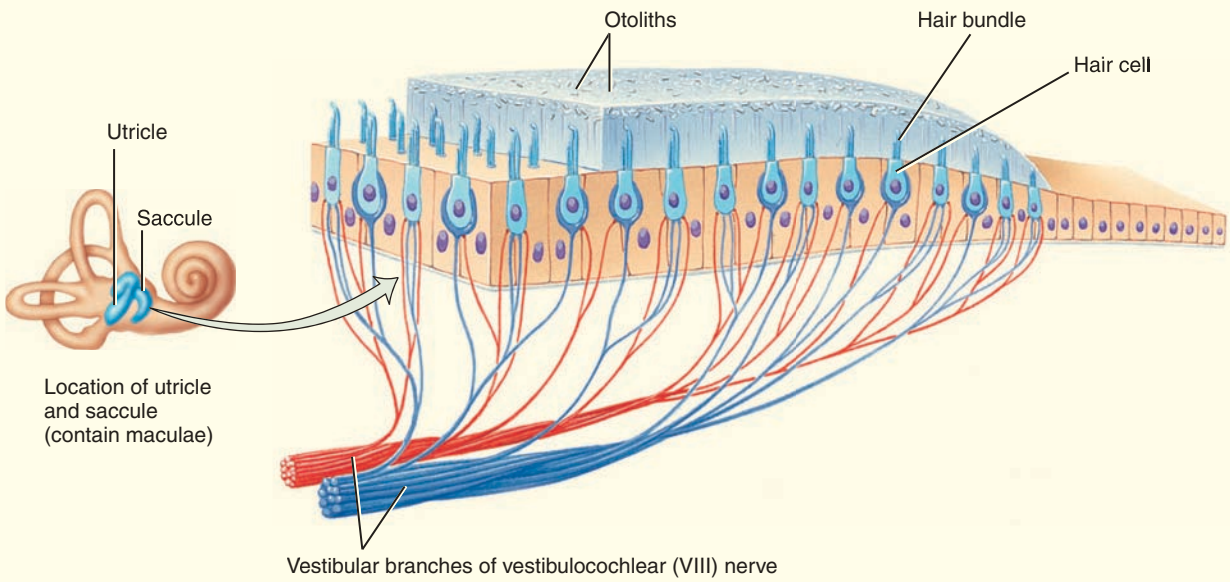
The entire middle and inner ear are actually within a hollow portion of the temporal bone.

The middle ear is filled with air and communicates with the external environment through the eustachian tube, or **auditory tube**. Air pressure must be almost equal on both sides of the tympanic membrane for it to freely vibrate in response to sound waves. When we pop our ears, we are actually opening the auditory tube, allowing air pressure to equilibrate on both sides of the eardrum.

The cochlea of the fluid-filled inner ear is a coiled tube, built like a snail shell. If we unwound it, the cochlea would be a straight tube, extending from the oval window at the beginning of the inner ear to the round window. The cochlear tube has three compartments. The uppermost compartment, continuous with the oval window, is called the **vestibular canal**. At the tip of the snail shell, this compartment rounds the end of the tube and forms the **tympanic canal** at the bottom of the cochlea. The tympanic canal ends at the round window. These two chambers form a U-shaped fluid-filled passage for the pressure waves generated at the oval window.

Within the center of the cochlea is a third chamber. This chamber houses the organ that converts mechanical vibration into sensory input, the **organ of Corti**. The

Inner ear structures of balance • Figure 8.4



a. The structures of static equilibrium

flattened **tectorial membrane** lies on top of the organ of Corti. The membrane rests on the top of hair cells, with the hairs, or **stereocilia**, just touching the membrane. The hair cells of the organ of Corti are directly linked to the **vestibulocochlear** nerve, cranial nerve VIII. Sound waves transferred to mechanical waves at the tympanic membrane are transferred to fluid waves at the oval window. These waves travel through the fluid of the inner ear as a pressure wave.

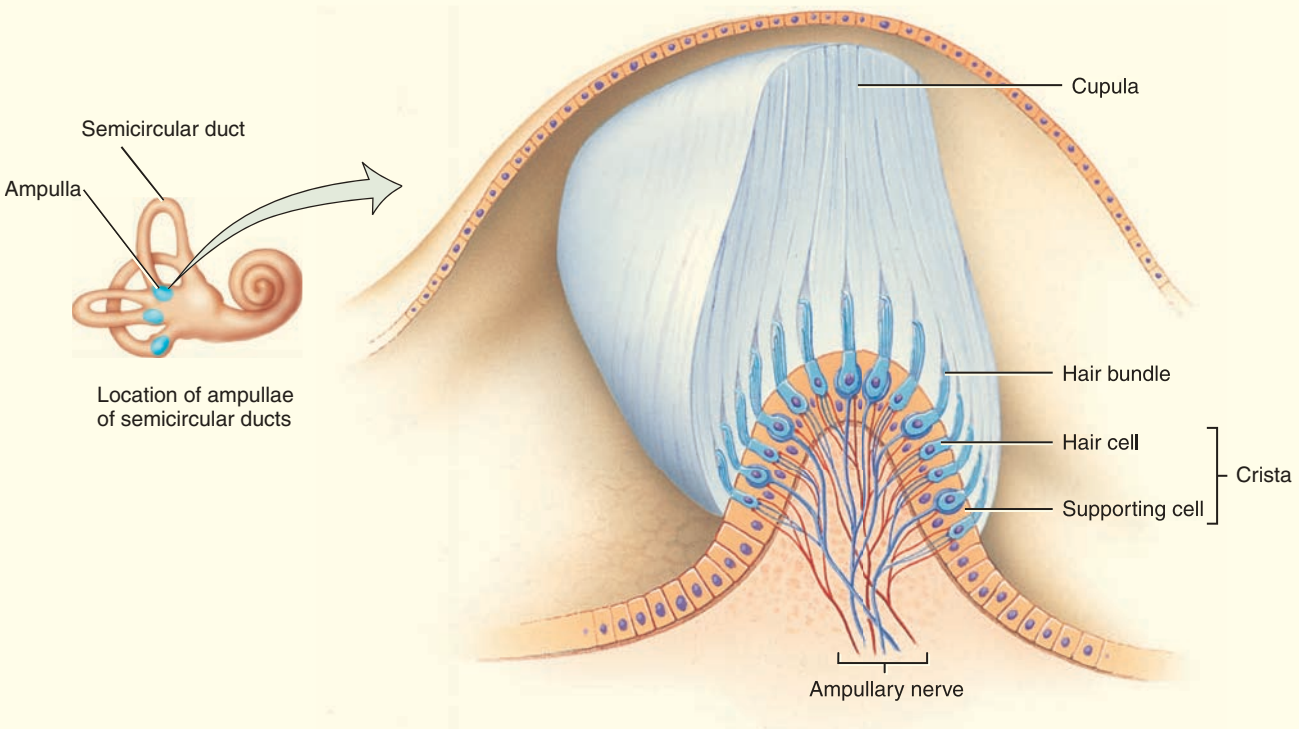
Each part of the tectorial membrane is sensitive to a different pitch. When the tectorial membrane is deformed by the passing pressure wave and the underlying hairs are bent, as happens in response to sound, a nerve impulse is created in the neuron of that particular hair cell. This impulse is carried to the brain, where it is interpreted as a particular pitch. Each part of the tectorial membrane is sensitive to a different pitch, allowing us to receive discrete information concerning the sounds we hear. Lower frequency noises vibrate the organ of Corti near the tip of the cochlea, whereas higher frequency noises cause vibrations at the base. The nerves from each portion of the cochlea lead to specific areas of the brain, further enhancing our ability to discriminate sounds.

Equilibrium Is Also Housed in the Inner Ear

Many people are surprised to learn that the sense of balance is also housed in the ear. The vestibule and semicircular canals of the inner ear house structures responsible for the two types of equilibrium—static and dynamic—as shown in **Figure 8.4**.

Static equilibrium is a response to gravity. Static equilibrium (also called gravitational equilibrium) is the physical response to gravity that tells us which direction is down. The **utricle** and **saccule** are structures located in the vestibule of the inner ear. Much as in the sense of hearing, these two structures initiate a nerve impulse when hairs within them bend. The utricle and saccule contain two gelatinous blobs situated at right angles to one another in the vestibule, called the **maculae**. Each of these organs contains tiny pieces of bone that respond to gravity. These organs are held in the vestibule by hair cells. The ends of the hairs are stuck in the gelatin, allowing the hairs to respond to movement of the organ.

The utricle and saccule are arranged at right angles to one another, so that when the head is upright one of them is vertical and the other horizontal. As gravity pulls on the vertical element, the hairs associated with it bend.



b. The structures of dynamic equilibrium

As before, this bending causes a nerve impulse to be generated, except that this impulse goes to the area of the brain that interprets static equilibrium. As head position changes with respect to gravity, these impulses change in frequency and direction, continually providing information on the up-and-down placement of your head.

Dynamic equilibrium is a response to changes in motion. Your sense of dynamic equilibrium (also called rotational equilibrium) detects acceleration or deceleration of your head. This sense originates in three semicircular canals situated so that each one lies in a separate plane: X (the horizontal plane, or the plane this book lies on when you lay it flat on the table), Y (the vertical plane, or the plane this book lies on when you stand it upright on the table with the spine facing you), and Z (transverse plane, or the plane that this book lies on when you again stand it upright on the table, this time with the cover facing you). The fluid in each tube rocks in response to acceleration in its particular plane. At the base of each semicircular canal is a swelling, called the **ampulla**. This swollen area houses the dynamic equilibrium receptor, a flame-shaped **cupula** of gel with hairs embedded. As the fluid in the semicircular canal rocks through the swollen base of the canal, it pushes on the cupula and bends its hairs, again sending a nerve impulse to the brain. These structures are responsible for the strange feeling you get in an elevator. The fluid in the canals responds to the acceleration of your head, but your eyes perceive no motion, so you get that familiar flipping feeling in your stomach.

CONCEPT CHECK STOP

1. **What** are the special senses?
2. **How** do neurons involved in the sense of taste obtain information?
3. **How** does sound travel through the outer, middle, and inner ear?
4. **What** common traits are there in the physiology of balance and hearing?

8.2 Vision Is Our Most Acute Sense

LEARNING OBJECTIVES

1. **Describe** the anatomy of the eye.
2. **Follow** the pathway of light through the eye.
3. **Explain** nearsightedness and farsightedness, listing the proper corrective measures.
4. **Discuss** the structure of the retina and the pathway of visual impulses from retina to brain.

We are visual creatures. We perceive the world primarily through our eyes, devoting a large percentage of our brain to the interpretation of visual images. Despite the enormous importance of our eyes, they are relatively simple structures and work like a very sensitive camera—see **Figure 8.5**. The eye regulates the amount of light that enters the photoreceptor area and then captures that light as an image. The brain captures and interprets that image, making sense of what is seen much like the chips in a typical digital camera.

The Eye Has Three Layers

The eye is an elongated sphere that has three layers: the **sclera** (or fibrous layer), the **choroid** (or vascular layer), and the **retina** (or the nervous layer). The outermost layer, the sclera, is composed of dense connective tissue forming both the white **sclera** and the clear **cornea**. The sclera is protected by the eyelids, eyelashes, and eyebrows, which prevent dust and particles from entering the eye.

The sclera provides a stiff outer covering for attaching the six extrinsic muscles that connect the eyeball to the bony orbit. **Lateral**, **medial**, **superior**, and **inferior rectus muscles** roll the eye left and right, up and down, in its socket, whereas the **superior** and **inferior oblique muscles** pull the eye obliquely. For example, when you contract your superior oblique muscle, your eye rolls downward and laterally. The oblique muscles also help stabilize the eye as it is pulled by the four rectus muscles.

The anterior sclera and cornea are bathed continuously by **lacrimal gland** secretions, or tears. These glands lie in the upper and outer corner of the eye. The tears wash across the eye and are collected in holes on either side of the nasal cavity.

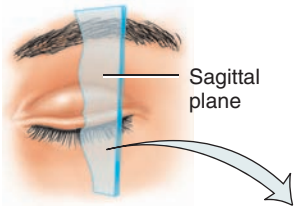
Immediately beneath the sclera is a dark-pigmented layer, the **choroid**. This layer houses the blood supply for the eye and contains melanin to absorb light. (Imagine how difficult it would be to interpret visual images if light bounced around inside the eye. With the light not absorbed, we would see repeated images, rather like a house of mirrors.) The choroid ensures that light strikes the **retina** only once.

The choroid is visible as the **iris**, the colored portion in the front of the eye. The iris is a muscular diaphragm that regulates light entering the eye. When contracted, circular muscles close down the **pupil**, whereas radial muscles dilate, or open, it. See **Figure 8.6**. The color of the iris is a reflection of the amount of melanin produced by the choroid. Dark eyes have more light-absorbing melanin on both sides of the choroid. Lighter eyes have less melanin on the underside of the choroid, which is what we see through the cornea.

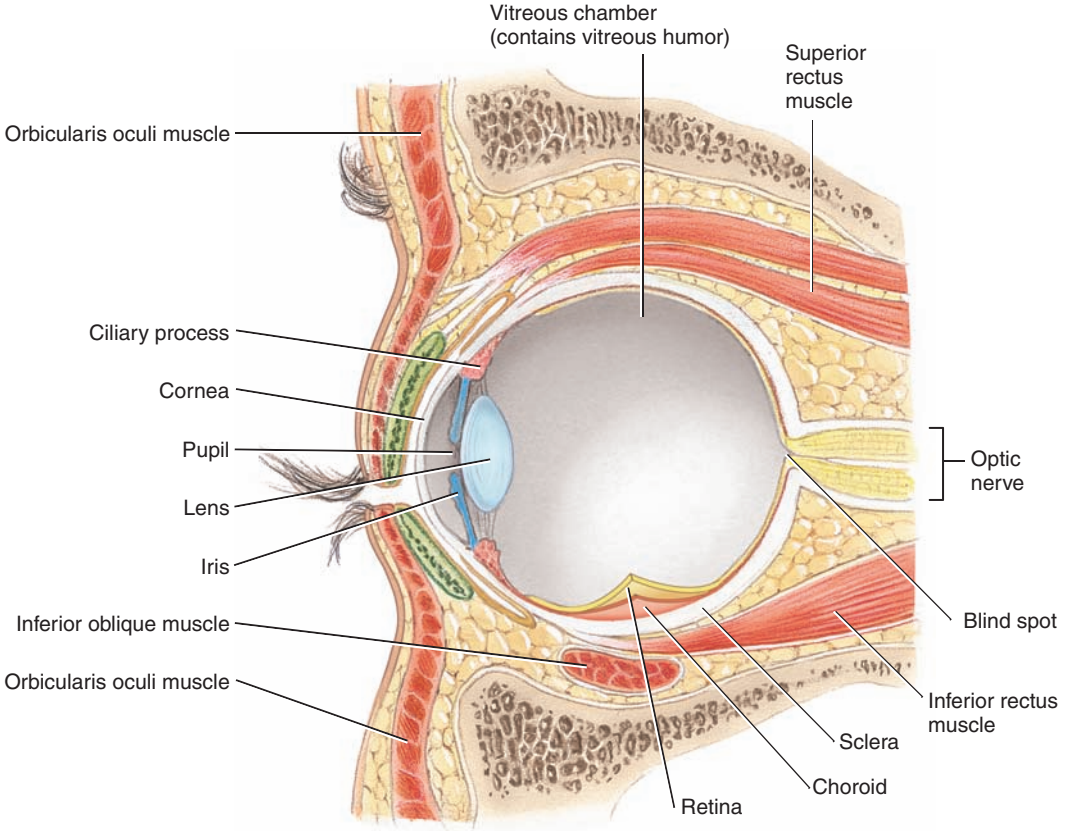
pupil The hole in the center of the iris.

Immediately behind the iris, the choroid thickens and becomes the **ciliary body**. This structure holds the lens in place, pulling it to change the shape of the lens to accommodate near and far vision.

Anatomy of the eye • Figure 8.5

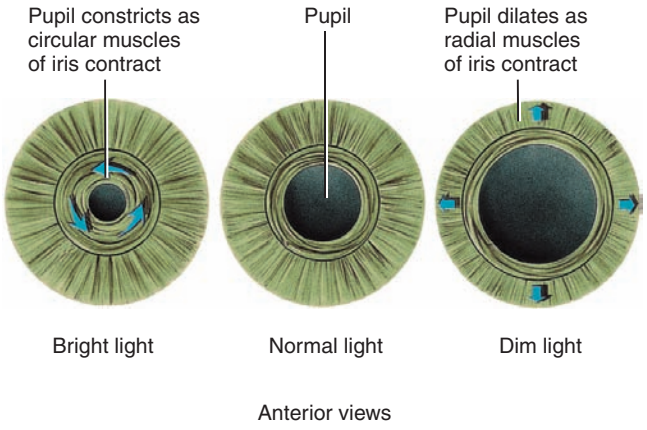


WILEY PLUS Video



The pupil responding to light • Figure 8.6

Circular muscles constrict the pupil, and radial muscles dilate it.



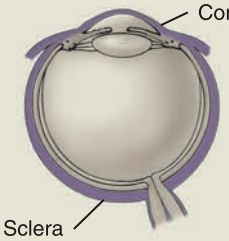
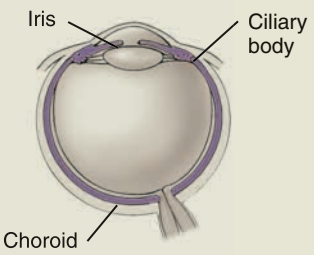
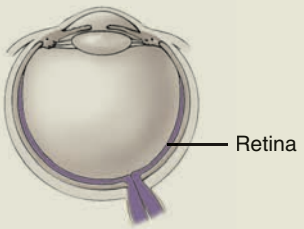
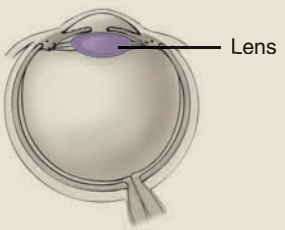
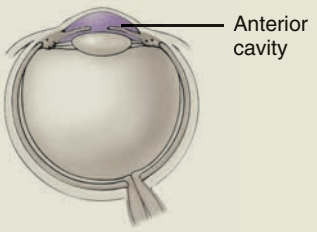
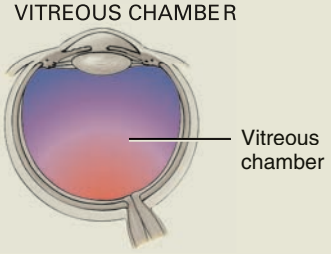
The lens and cornea are both bathed in **aqueous humor**, a fluid that is constantly filtered from the blood. The aqueous humor is returned to the blood via the canal of Schlemm, at the junction of the cornea and the sclera. These canals get constricted in glaucoma, causing an increase in pressure that can eventually destroy the light-sensitive cells in the retina. See **Table 8.1** for a complete listing of the structures of the eye and their functions.

The Lens Changes Shape to Achieve Optimal Optics

Visual acuity requires the eye to focus entering light onto the retina at the back of the eyeball. The lens and the cornea both focus light rays so that they converge on the retina. The lens, immediately behind the pupil, is held inside a connective-tissue covering that connects directly to the ciliary body. When the muscles of the ciliary body contract, the entire ring of the ciliary body gets smaller. This releases pressure on the connective tissue covering the lens, and the lens bulges, creating more focusing power to see nearby objects. When the muscle relaxes, the ring of the ciliary body enlarges, pulling the lens flat and enabling the eye to focus on faraway objects, as shown in **Figure 8.7**. The changing of lens shape to view nearby objects is called **accommodation**, which gets more difficult with age. The reason is that with each passing year, the lens

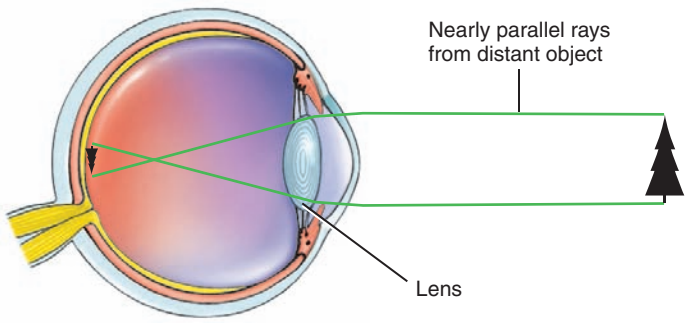
visual acuity The resolving power of the eye.

Eye structures and their functions Table 8.1

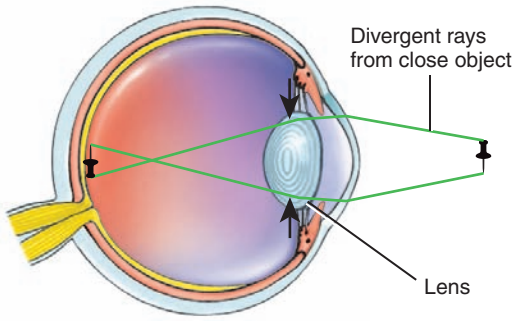
FIBROUS LAYER 	*Cornea*: Admits and refracts light. *Sclera:* Provides shape and protects inner parts.
VASCULAR LAYER 	*Iris:* Regulates amount of light that enters eyeball. *Ciliary body:* Secretes aqueous humor and alters shape of lens for near or far vision. *Choroid:* Provides blood supply and absorbs scattered light.
NERVOUS LAYER 	*Retina:* Receives light and converts it into nerve impulses. Provides output to brain via ganglion cells, which form the optic (II) nerve.
LENS 	*Lens:* Refracts light.
ANTERIOR CAVITY 	Contains aqueous humor that helps maintain shape of eyeball and supplies oxygen and nutrients to lens and cornea.
VITREOUS CHAMBER 	Contains vitreous humor that helps maintain shape of eyeball and keeps the retina flat against the choroid.

Visual accommodation • Figure 8.7

When the eye is focusing on a faraway object, the lens flattens because less focusing power is needed. When an object is close, the lens bulges to increase the focusing power.



a. Viewing distant object



b. Accommodation

continues to add layers that resemble the layers of an onion. These extra layers make the lens thicker and stiffer, so it resists curving to focus on nearby objects when the ciliary body relaxes. Starting around age 45 or 50, this curving becomes so difficult that many people need reading glasses. The glasses enlarge the image before it reaches the pupil, giving the lens a larger image to bring into focus.

Common visual impairments are nearsightedness, farsightedness, and astigmatism. Nearsightedness and farsightedness are both caused by the lens's inability to accommodate light properly. In nearsightedness, the eye is too long for the lens to focus the light rays on the retina. The focal point of the eye, the point at which the image is in focus, winds up in the vitreous humor (the fluid in the back chamber of the eye), and the image is spreading out and fuzzy again when it hits the retina. A concave lens will spread the light rays farther before they enter the eye, correcting this problem. Farsightedness is the opposite of nearsightedness. In farsightedness, the lens focuses the image from the pupil behind the retina. A corrective convex lens will begin the process of focusing the light rays before they enter the eye, moving the focal point forward to the retina itself.

Astigmatism is another common abnormality of the eye. In this case, the cornea is imperfectly shaped, resulting in an uneven pattern of light hitting the retina. Some areas of the image are in focus but others are not. A carefully crafted lens that compensates for the uneven flaws of the cornea can correct this problem. See **Figure 8.8** on the next page.

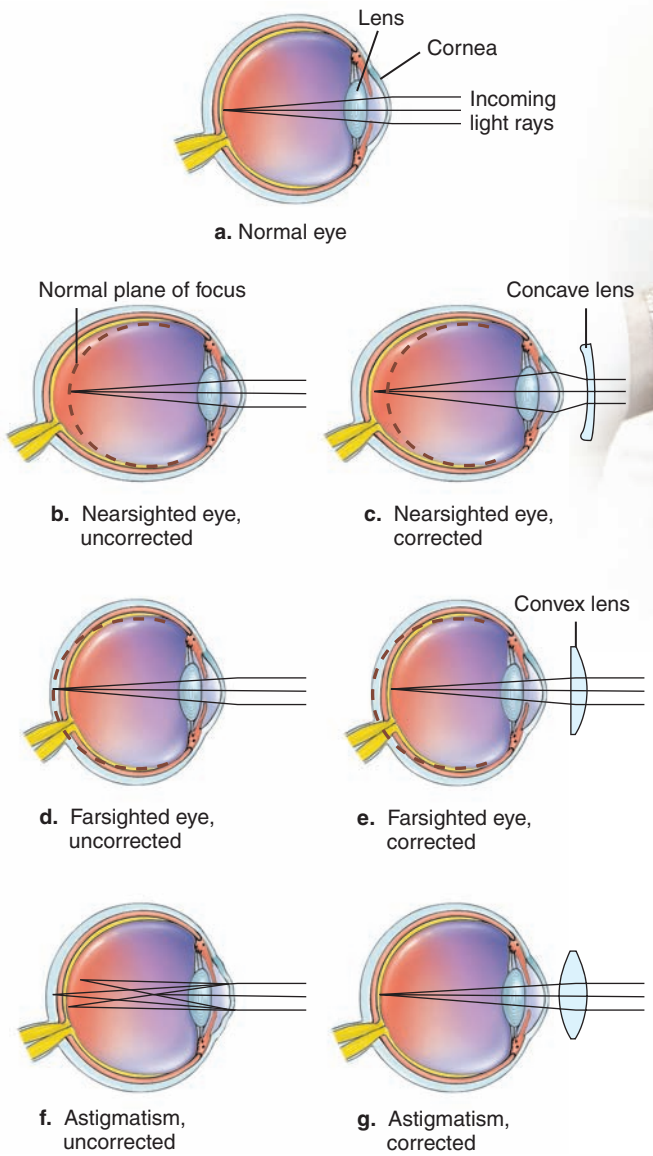
Eyeglasses and contact lenses are the traditional technologies to help the lens and cornea focus. Today, corrective surgery is becoming a more viable method to reshape the cornea to achieve visual acuity.

Photoreceptors Detect Light in the Retina

Behind the lens lies a large chamber filled with **vitreous humor**, a gel-like fluid that holds the third layer of the eye, the retina, in place. The retina spreads out over the inside rear of the eye, somewhat like the cloth of an umbrella spreads over the umbrella frame. Unlike the umbrella cloth, however, the retina is not physically attached to the back of the eyeball except at its center, where a blind spot is located. There are no photoreceptors in the blind spot of the retina, because this is where the optical nerves dive through the retina toward the brain. The blind spot is also called the optic disk. Retinal neurons line the surface of the retina that is exposed to the vitreous humor, with the photoreceptors at the back and directed toward the brain.

The vitreous humor maintains slight pressure on the retina, pressing it flat against the back of the eye. Because it is not attached, the retina can be "detached" if the eye is hit hard enough to slosh the vitreous humor—even a momentary movement may allow the retina to fold. If this happens, light cannot reach the photoreceptors inside the fold, so they detect nothing.

Common visual impairments • Figure 8.8



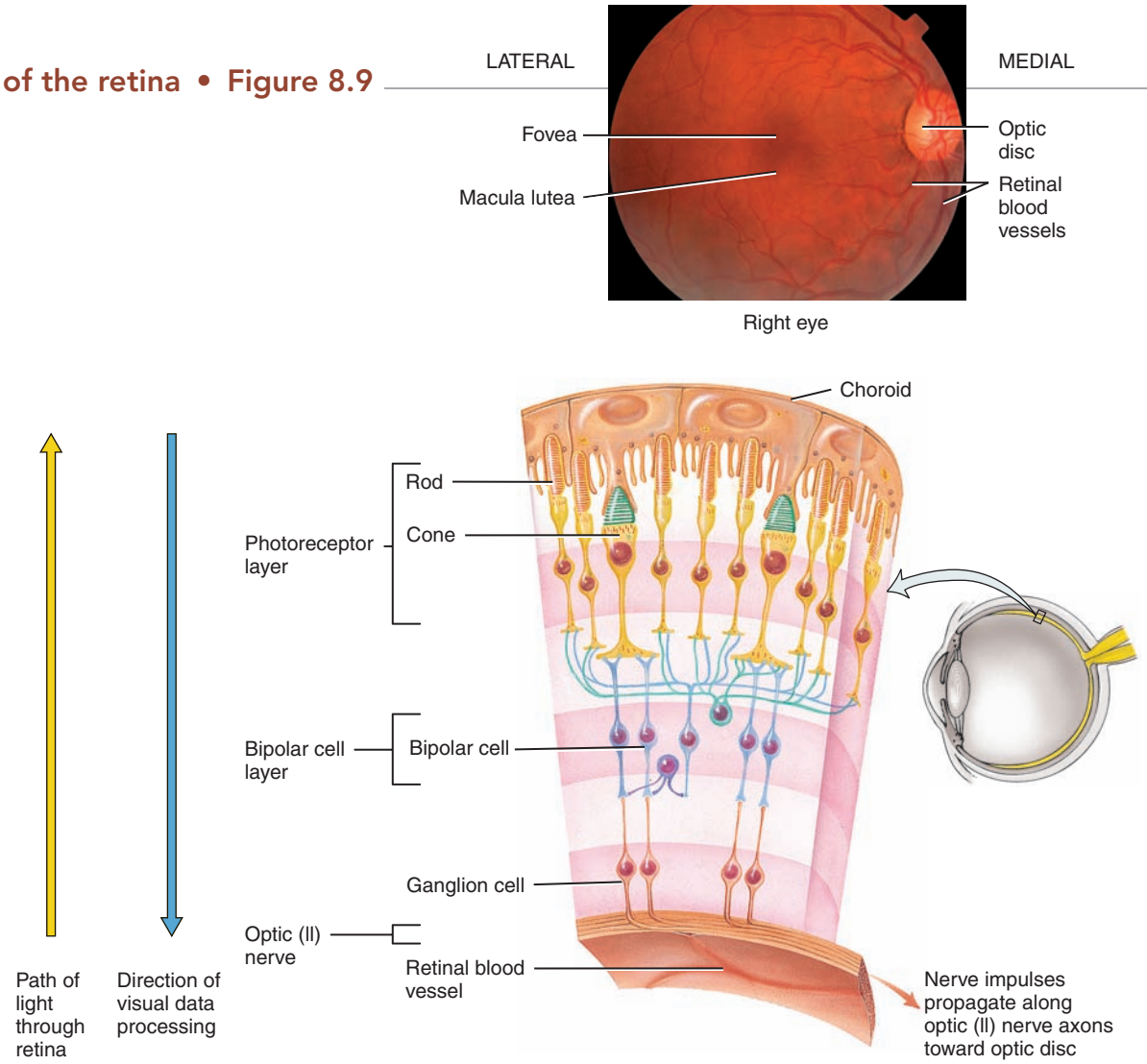
Vision check-ups are an important part of maintaining good health. Visual acuity and astigmatism are routinely monitored during a simple eye exam. Visual acuity is determined by reading successively smaller type until the letters are too blurred to distinguish. Astigmatism can be diagnosed by observing a diagram of a wheel with spokes extending in all directions. If a few of these spokes are not distinct, the eye may be out of round in those areas.

The retina, as shown in **Figure 8.9**, is composed entirely of neurons in layers containing rods and cones, bipolar cells, and ganglionic cells. The rods and cones are the neurons that detect light—the photoreceptors. The bipolar cells and ganglionic cells are interneurons that carry the action potential generated by the photoreceptors to the brain. The cones respond to bright light, providing color vision and resolution that is high enough to allow us to distinguish tiny individual structures, such as human hairs. The rods function in low levels of light, providing only vague images. These two types of cells are unevenly distributed. Cones are concentrated near the center of the retina, where incoming light is strongest. In fact, the area of the retina immediately behind the pupil is slightly yellow owing to the high concentration of cones, and it is called the **macula lutea**. This area provides our highest resolution, allowing us to discriminate subtle differences in objects needed, for example, to read. At the very center of the macula lutea is the fovea (also named the fovea centralis), which consists only of cones and is where light is focused when we look directly at something. Rods are spread across the periphery of the retina. The rods are not terribly good at resolution, but they do respond in extremely low light.

macula lutea The area of the retina immediately behind the pupil (*macula* = spot; *lutea* = yellow).

The layers of neurons in the human eye seem backwards, because the photoreceptors are against the back of the eye, oriented toward the brain rather than toward the source of light. Light rays must pass through the entire retina before they stimulate the photoreceptors at the back. This so-called indirect retina is found in most mammals. Interestingly, the squid and octopus have eyes that are anatomically very similar to our own, except that they

Anatomy of the retina • Figure 8.9



do NOT have an indirect retina. Their photoreceptors are directly behind the vitreous humor, so light strikes them first. As a result, they do not have a blind spot, which is doubtless helpful in the dim ocean depths.

Rods and cones operate using different chemical mechanisms. When a photon of light hits a rod, a neural response is initiated via the chemical **rhodopsin**. The energy from the photon splits rhodopsin into two compounds (retinal and opsin), releasing energy that starts a series of events ultimately resulting in a closing of ion gates on the photoreceptor membrane. When the ion gates on the photoreceptor close, ion movement ceases, an action potential is generated, and the brain receives a single bit of visual information.

rhodopsin Visual pigment that responds to low levels of white light.

Rhodopsin is easily **bleached**, meaning that a slight increase in light can cause it to fall apart and not be able to recombine. Until the light is reduced, rhodopsin cannot regenerate. As a result, the rods cannot detect another photon when in bright light. If rhodopsin is not put back together, there can be no further action potentials.

When you stargaze, you are using rods. You may know that to see an especially dim star, it's better to focus to one side of the star. Why? It is because rods are not found directly behind the pupil but rather on the periphery of the retina. The dim starlight is not strong enough to stimulate the cones directly behind the pupil, but it is strong enough to stimulate the rods. You may also be aware that you see far more stars after 15 to 20 minutes of looking at the heavens. After this period, bleached rhodopsin has entirely re-formed in the rods.

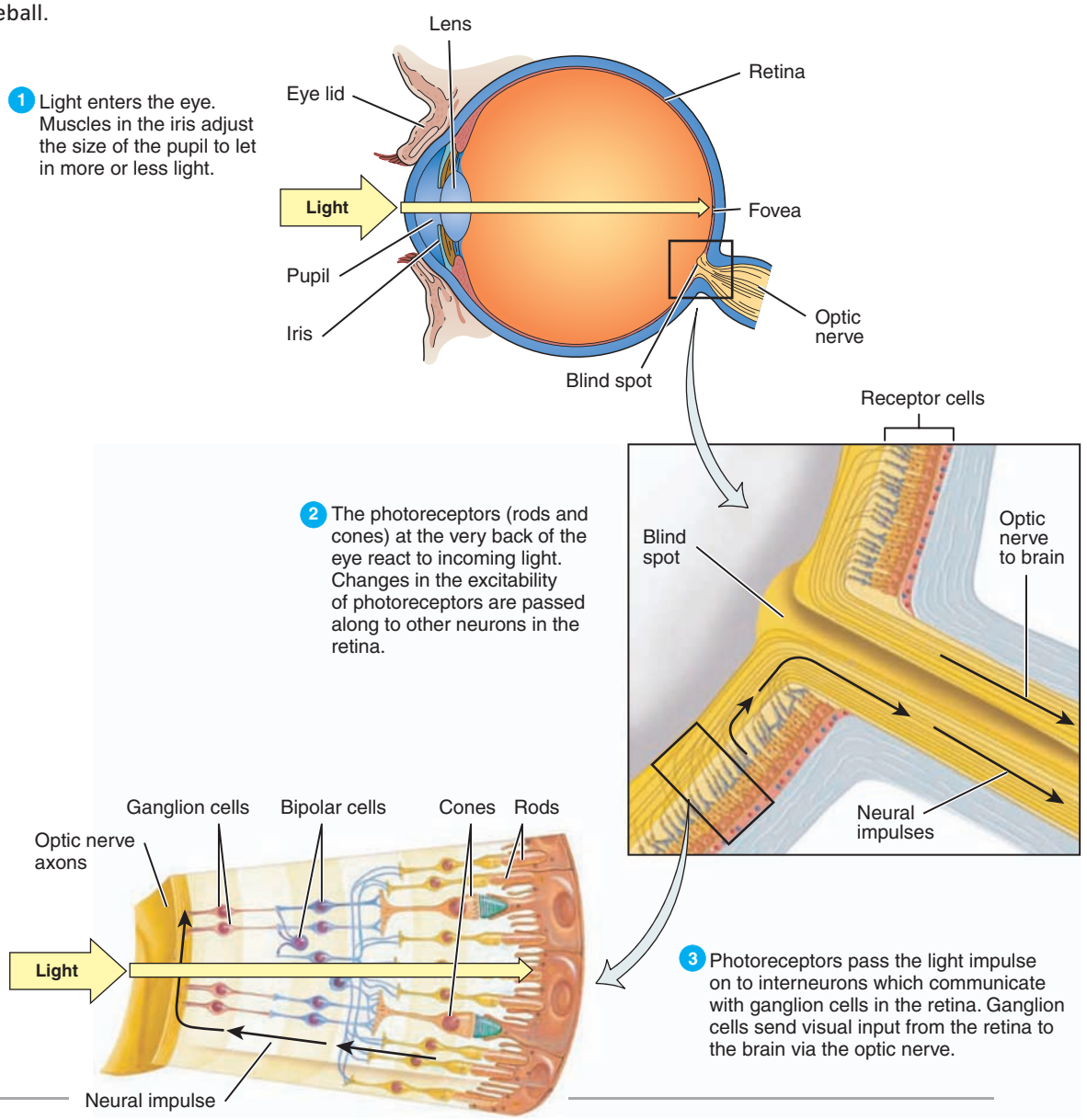
Cones—the source of fine-detailed color vision. You have three types of cones, which are sensitive to different wavelengths of light, representing red, green, or blue. Cones also use the visual pigments retinal and opsin but with slight variation. Although the retinal and

PROCESS DIAGRAM

Photoreceptor impulse generation • Figure 8.10

THE PLANNER

Light enters the eye through the cornea and then is focused on the retina by both the iris and the lens. It travels through the vitreous humor, striking the retina and working its way to the back of the eyeball. There, light stimulates the rods and cones, which in turn send their impulse to the bipolar neurons. The impulse is then sent to the ganglionic neurons and then to the occipital lobe of the brain via the optic nerve.



opsin in rods fall apart and do not regenerate in bright light, these chemicals readily regenerate in the cones.

These physiological responses explain how our eyes respond to sudden changes in light. When the lights first go down in a movie theater, they dim slowly to give our eyes time to adjust to the dark. The rhodopsin in the rods, which had bleached in the bright light, gets time to regenerate. After the rods resume working, we can see nearby chairs even in near darkness. Cones respond almost immediately to brightening light. If you leave a theater, you can soon see in the lobby. However, if you reenter a dark theater, you may experience momentary panic because the sudden dark effectively blinds you. If you exit a dark theater for the sunlit outdoors, the rhodopsin in your rods, which were providing vision in low light, suddenly bleaches, sending information to your brain that you experience as a "white flash." In the bright light, rhodopsin cannot regenerate, and the rods remain defunct, but cones will quickly start sending impulses to the brain, your pupils will close, and your vision will be restored.

Visual Nerve Impulses Travel to the Brain

Regardless of whether the visual nerve impulse comes from a rod or a cone, it travels from the retina to the brain in basically the same pathway. The impulse first passes toward the front of the eye, from the photoreceptors to the bipolar neurons. These bipolar neurons transmit the impulse to the ganglionic cells in the anterior of the retina. Ganglionic cells collect impulses from a small cluster of bipolar cells and pass them to the brain via the optic nerve. See **Figure 8.10**.

The ganglionic cells are in the front of the retina, and the brain is behind it. To reach the brain, axons of the ganglionic cells must penetrate the retina, which they do by literally diving through the retina. This location can have no photoreceptors, which explains why a blind spot is located just off-center in each eye. We generally do not recognize the blind spot owing to our **stereoscopic** vision. Each eye sees a slightly different view of the world because the eyes are placed slightly apart, angled just a little bit away from one another. Our brain melds these two views into one continuous field of vision. Objects that fall on the blind spot of the right retina are seen by the left retina, and vice versa. The brain fills in the missing details from each view, providing us an unobstructed perception of our environment and disguising the blind spot.

stereoscopic Depth perception gained through use of the visual field of both eyes.

Exactly how the brain interprets the flood of information it receives from the eyes is a field of study in and of itself. Vision is so important that it occupies more space in the brain than any other special sense. We know that visual impulses travel along the optic nerve, through the thalamus to the occipital lobe of the brain. Some impulses cross to the opposite side of the brain at the **optic chiasma**. The view from the right eye is partially projected on the left side of the visual cortex of the cerebrum, and the view from the left eye is partially projected on the right side. Additionally, the image reaching the occipital lobe is upside down and inverted. The brain must flip and invert the image before it makes sense to us. All of this occurs continuously and almost instantaneously, without your even knowing it.

optic chiasma The physical crossing of the left and right optic nerves.

CONCEPT CHECK

STOP

1. **What** are the three layers of the eye and **what** does each consist of?
2. **What** structures does light pass through in the eye as it reaches the retina?
3. **What** causes nearsightedness and farsightedness, and **how** are they treated?
4. **How** are impulses carried from the retina to the brain?

8.3 The Special Senses Are Our Connection to the Outside World

LEARNING OBJECTIVES

1. **Discuss** how society views sensory loss.
2. **Differentiate** between conduction deafness and nerve deafness.

Our special senses are literally our connection to the world around us. They have a profound effect on us in ways we may not even consciously know (see *Health, Wellness, and Disease: Using Our Special Senses to Promote Healing*).

Although aging may impair many of the special senses, most people still lead productive, active lives even with this slight declining in their ability to perceive the world. The chemical senses decline with age, causing a noticeable loss in our ability to perceive odors and tastes. There is no "fix" for this loss, other than adding additional spices to foods and increasing the amount of fragrances used. Mild eyesight defects are usually easy to correct with eyeglasses. In fact, an entire market has been created for designer eyewear. Also,

HEALTH, WELLNESS, AND DISEASE

Using Our Special Senses to Promote Healing

Hospitals and other healthcare facilities built in the next twenty years may bear only a slight resemblance to those built more than 20 years ago. A new generation of architects is trying to appeal to our special senses more than ever before, based on mounting evidence that patients with a view of a natural setting have a shorter recovery time and take fewer painkillers than those with a view of a brick wall. Those whose rooms have more windows often have a greater sense of wellness than those whose rooms have fewer or no windows.

Today, many hospitals and hospices are designed so that every patient has a view to the outside, and multistory lobby atriums with plentiful natural light, views of waterfalls, courtyards, and Zen gardens are becoming commonplace. Basements are being banished, except for storage!

Interestingly, the trend is to increase these special senses' healing effects by decorating hospital rooms with idealized landscapes with plenty of animals and flowers (much preferred by patients over abstract art, according to most evidence). Also, systematic research has shown conclusively that some colors, such as greens and blues, calm residents or patients, while other colors agitate them. Our special senses are so in tune with signals from our natural environment that they sometimes don't distinguish between art and reality.

several surgical techniques, such as laser eye surgery, can improve the focusing of light rays, permitting many to see well without corrective lenses. See *What a Scientist Sees: Laser Eye Surgery* for more on this procedure.

Complete loss of sight is another story, however. The blind are not easily assimilated into mainstream culture. As mentioned earlier, we humans are extremely visual organisms, relying mainly on sight to get us through the world. Our social and economic systems require us to pick up visual cues, leaving blind people to function in a society designed for the sighted. Despite the use of braille on elevator buttons and a few restaurant menus,

Seeing Eye dog • Figure 8.11

Many visually impaired people rely on Seeing Eye dogs to assist them in their daily chores. These dogs are trained to walk in a harness, alert their owner to the presence of curbs or other dangers, and make intelligent decisions on whether it is safe to comply with the commands of their owner. For many, these dogs permit them to lead full and productive lives.

many blind people must obtain aid from a sighted person or a Seeing Eye dog to function, as shown in **Figure 8.11**. Simply getting around can be challenging. Read about the cost of eye care in developing countries in *Ethics and Issues: Let There Be Sight*.

Like Vision, Hearing Can Diminish with Age

Some hearing loss is due to mechanical malfunctions. In **conduction deafness**, sound is poorly conducted from the outer ear to the inner ear, as would happen, for example, if the ossicles were prevented from moving easily. Hearing aids can help those with conduction deafness by increasing the amplitude of sound that enters the ear. However, deafness is often due to neurological malfunction rather than a conduction problem. If auditory troubles are caused by **nerve deafness**, a hearing aid does not help, because the problem is that the sound is either not detected by the cochlear nerves or the nerve impulse is not transmitted to the brain. Cochlear implants convert sound vibrations into electrical impulses and have shown some promise in treating nerve deafness.

NATIONAL GEOGRAPHIC

WHAT A SCIENTIST SEES

Laser Eye Surgery

LASIK (Laser-Assisted in Situ Keratomileusis) surgery refers to the use of lasers to alter the shape of the cornea. A small flap of cornea is cut and lifted back, exposing the center of the cornea. This middle corneal tissue is then vaporized in small, precisely controlled sections, causing the cornea to lie in a shape conducive to clear vision when the flap is replaced. Radial keratotomy is essentially the same process, except that instead of lifting a flap of cornea, the outer layer is removed completely.

Think Critically

1. How will removing some of the corneal tissue affect the rays of light passing through to the lens?
2. Can radial keratotomy correct for the farsightedness that occurs with age?
3. Why might ophthalmologists caution people who are interested in using this procedure specifically to reduce their need for reading glasses to wait until they reach at least 55?

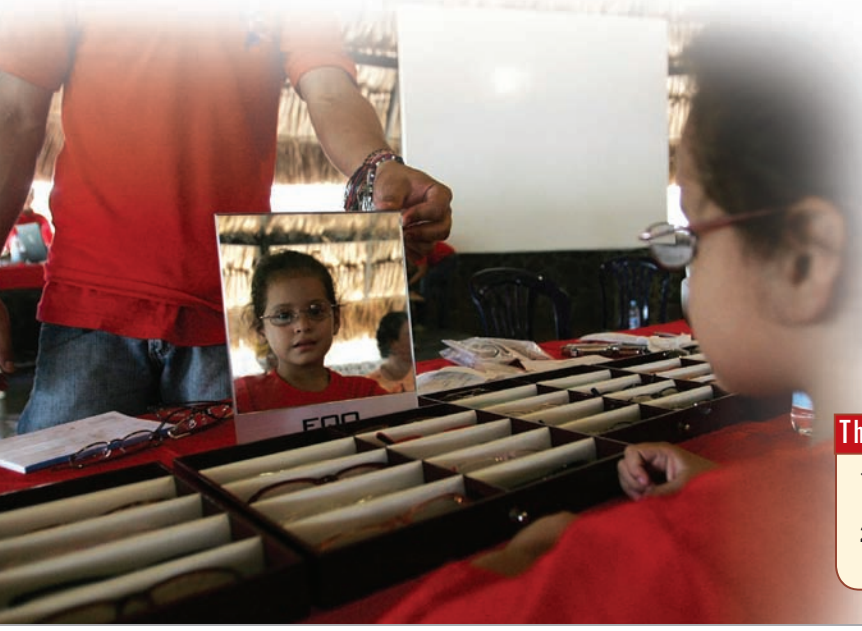
ETHICS AND ISSUES

Let There Be Sight

We are visual organisms. We perceive and interpret the world directly through our sense of sight. We invent methods of illuminating the darkness in order to see at all times. Hearing is important, but it often plays an ancillary role to the information we receive from our eyes.

Despite the fact that eye care in the United States is relatively easily accessible, many people do not get regular exams. Optometrists are located in shopping centers and malls. Corrective eyewear can be prescribed, created, and worn in under an hour. Contact lenses can be ordered online. Vision testing is required in public schools in 35 states. Many of these states provide free vision testing, with reduced cost follow-up eye care for those in need.

Of course all of this comes at a price. The frames for many glasses are extremely expensive, and in order to purchase a pair of glasses or a set of contact lenses, the patient must present a medically approved prescription written within the year. In 2006, the North Carolina courts blocked the North Carolina School Boards Association ruling to provide eye tests for every student due to the high costs, estimated at $120 per exam.



According to World Health Organization's 2007 report, more than 464 million people suffer from easily correctable eye disorders. Many organizations are working to provide both eye exams and corrective lenses to third world countries. Lions Clubs International collect used eyeglasses and restore them so that others may use them. They work in conjunction with other nonprofit organizations to identify areas across the globe where free eye clinics might be set up. One such organization, Give the Gift of Sight, provides free eye care and glasses in developing nations. This organization began in 1991 with a small, two-week clinic that assisted over 8,000 Costa Ricans. Over the past 20 years, Give the Gift of Sight has helped more than 2.5 million people in 32 developing nations to see more clearly.

Of course, there must be some money behind this sort of generosity. Who is paying for the physician's time, the administration of the clinics, the shipping of the free glasses, and the room and board required by the clinic's staff? Interestingly, Give the Gift of Sight is underwritten by a large manufacturer of prescription eyewear.

What if there was another solution to this problem? Professor Joshua Silver of Oxford University recently designed eyeglasses that can be "adjusted" to correct for nearsightedness or farsightedness. The lenses come with an attached syringe filled with a small amount of fluid. The end user is able to add or subtract fluid from the center of these lenses to achieve clear vision. More fluid creates a thicker lens, correcting farsightedness. Less fluid results in a convex lens that will aid nearsighted patients.

Critical Reasoning Issues Are some of the costs associated with prescription eyeglasses reflective of the amount companies pay to provide "free" eye clinics in third world countries? Does that seem like a fair practice to you?

Think Critically

1. How might Professor Silver's invention change the lives of visually challenged people in third world countries?
2. How might it affect the vision care industry in the United States?

Just like blindness, deafness can be life threatening. Sirens, smoke alarms, even the ringing of a phone are all auditory cues that warn us of danger. Visual cues, such as flashing lights, have been added to most fire and hazard alarms in public buildings to assist those with hearing loss. In addition, many phones are available with a visual ring cue.

CONCEPT CHECK STOP

1. **How** does society view sensory loss?
2. **What** is the difference between conduction deafness and nerve deafness?

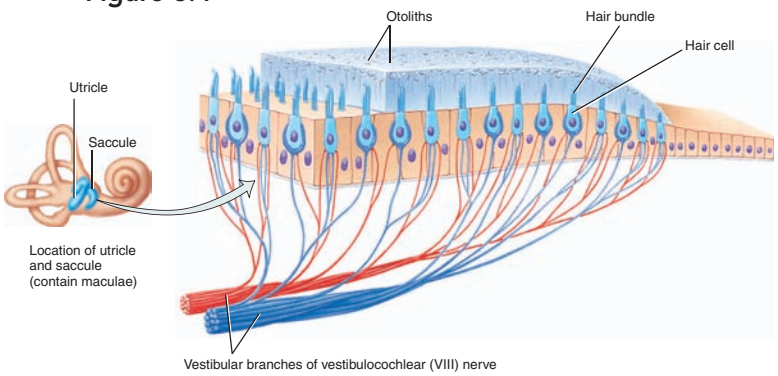
Summary

THE PLANNER

1 The Special Senses Tell Us About Our Environment 190

- Special senses include smell, taste, hearing, balance, and vision. Smell and taste are chemical senses, requiring that a compound be dissolved in mucus before being sensed.
- In the ear, sound waves are converted into mechanical motion, and then nerve impulses travel to the brain.
- As shown, static equilibrium is monitored by the maculae in the saccule and utricle, and the cristae of the semicircular canals provide our sense of dynamic equilibrium. Taste originates at chemoreceptors on the tongue, and smell (olfaction) originates in chemoreceptors in the nose.

Figure 8.4



2 Vision Is Our Most Acute Sense 196

- Vision begins with the eye, where light is converted to nerve impulses, and concludes in the occipital lobe of the brain, where these impulses are organized and interpreted. Vision is the best developed of the special senses in the human, and its interpretation occupies more of the brain than any other special sense.
- As you can see here, the pathway of light through the eye begins with the cornea and aqueous humor. Light passes through the pupil, is focused by the lens, and strikes the retina. When there are problems focusing the light rays, glasses or laser surgery can help.

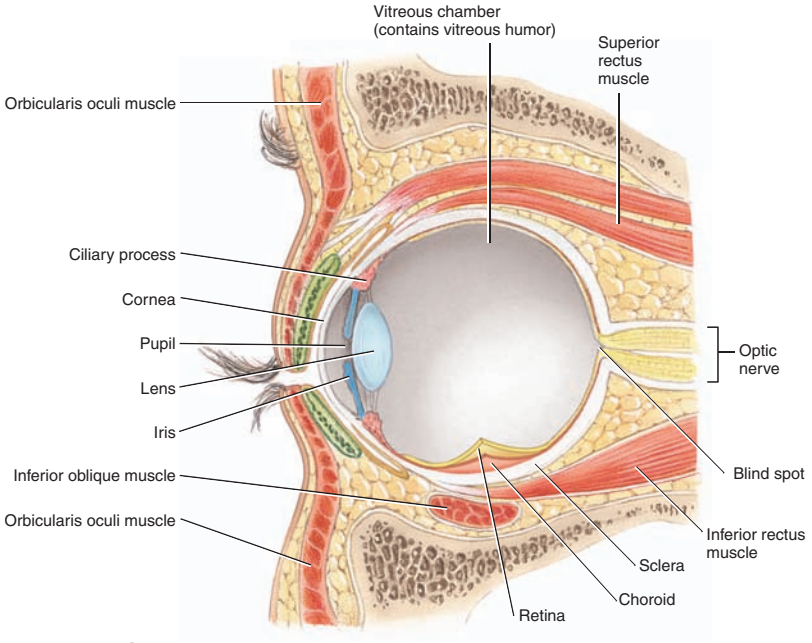


Figure 8.5

3 The Special Senses Are Our Connection to the Outside World 203

- Loss of visual or auditory acuity causes difficulty functioning in our society. We are visual beings—everything from road signs to menus to walking paths are designed for the sighted. Braille is used to present text messages to those who cannot see well enough to read, and trained dogs give the blind a degree of independence in a sighted world.
- Deafness can be caused by conduction problems or neurological malfunction. Hearing aids and cochlear implants can restore hearing to many patients.

Key Terms

- gustation 191
- macula lutea 200
- olfaction 191
- optic chiasma 203
- pupil 197
- rhodopsin 201
- stereoscopic 203
- uvula 192
- visual acuity 198

Critical and Creative Thinking Questions

1. Some people are born with a condition in which the cribriform plate of the ethmoid bone is not formed properly. The tiny perforations that allow the olfactory neurons to extend into the upper nasal passageway are not present, and the cribriform plate is instead a solid bone. How would this affect the sense of smell? The sense of taste?
2. **CLINICAL CLICK QUESTION**
   Raul and Maria were frustrated with the eating habits of their oldest child, Emanuel. He simply would not eat most vegetables, and avoided fruits such as cherries, plums, and even apples. Worried that their son would develop health issues due to his poor nutrition, they took him to a dietician. During testing, the dietician discovered that Emanuel enjoyed eating baby foods, but when presented with foods prepared for a more adult palate he simply could not eat them. Chocolate, sweets, and fatty foods, usually offered as treats for children, were also distasteful to Emanuel. Some foods even caused him physical pain. Just a small amount of black pepper in a dish would cause him to cry out that his mouth was burning. What special sense might be at the root of this aversion to many foods? Do you think Emanuel's chemical senses are not working properly or perhaps are working too well? How might you help his family to overcome this issue so that he is able to obtain proper nutrition? To help with your diagnosis and prescription, visit http://ysm.research.yale.edu/article.jsp?articleID=77. There you will find a scientific article from Yale Scientific on supertasting and nontasting.
3. When you ride an elevator, why does your stomach feel like it is "dropping" when you ascend? Which sensory organ(s) account for this sickening feeling, and what perceptual conflict helps create it?
4. A cataract is a clouded lens, usually associated with age. How would a cataract affect vision? Trace the pathway of light of entering an eye with a cataract, listing possible effects of the clouded lens. From what you know about the pathway of light through the eye, what might correct these visual disturbances?
5. Why do hearing aids not help a person suffering from nerve deafness? What is the difference between nerve deafness and conduction deafness? Which is easier to correct, and why?

What is happening in this picture?

At one point or another, we have all been in difficult situations like this one. While learning to drive, we had to focus on the visual signals we received, the auditory signals from both outside the vehicle and inside, and the tactile signals from our skin as we gripped the wheel, pushed the pedals, and sank into the seat.

Think Critically

1. Which sensory stimulus is most important when learning this task? Why is driving a car a difficult task to master?
2. Which sensory stimulus do we rely upon most once the skill is learned?
3. Why, specifically, do many states now have the "hang up and drive" law? Which of the special senses are compromised by those who choose to use their cell phones while driving?

Self-Test

1. All of the following are special senses EXCEPT _____.
   a. vision
   b. equilibrium
   c. olfaction
   d. proprioception

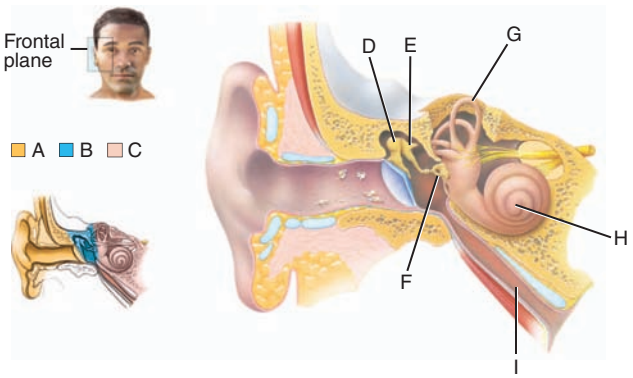
2. Which of the following senses involves mechanoreceptors?
   a. smell
   b. taste
   c. touch
   d. balance
   e. Both c and d are correct

3. The structure seen in this figure is a(n) _____.

   a. olfactory neuron
   b. gustatory neuron
   c. taste bud
   d. retina

4. Which of the following is NOT a category of taste that the taste buds can distinguish?
   a. salty
   b. sour
   c. bitter
   d. fruity

Questions 5–8 relate to this figure:



5. What is the function of the area(s) labeled A?
   a. to collect and transmit sound
   b. to convert sound waves to vibrations
   c. to dampen loud sounds
   d. to equilibrate pressure on either side of the tympanic membrane

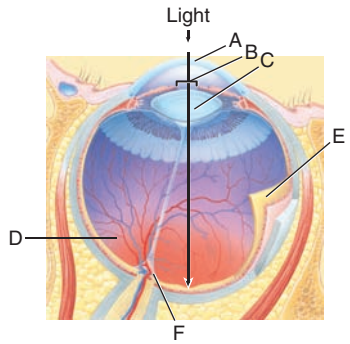
6. The function of the structure labeled G involves _____.
   a. hearing
   b. static equilibrium
   c. dynamic equilibrium
   d. olfaction

7. Which area is responsible for transmitting sound waves into vibrations?
   a. A
   b. B
   c. C
   d. I

8. The function of the structure labeled H involves _____.
   a. hearing
   b. static equilibrium
   c. dynamic equilibrium
   d. olfaction

9. The layer of the eye that includes the whites and the cornea is the _____.
   a. retina
   b. sclera
   c. innermost layer
   d. choroids

Questions 10 and 11 require the use of the following diagram:



10. What is the name of the structure labeled as E?
    a. aqueous humor
    b. choroid
    c. lens
    d. vitreous humor
    e. retina

11. What is the function of the structure labeled B?
    a. to focus light entering the eye
    b. to direct the amount of light entering the eye
    c. to send light rays on the retina
    d. to send visual impulses to the brain

12. Correction for farsightedness usually requires _____.
    a. a concave lens
    b. a convex lens
    c. laser surgery to reshape and smooth the cornea
    d. a carefully crafted lens that matches the contours of the cornea

13. The cones allow us to see indistinct shapes in low light, but they bleach and are ineffective when light levels increase.
    a. True
    b. False

14. The correct sequence of layers of neurons in the retina, from anterior to posterior in the eye, is _____.
    a. bipolar neurons → ganglionic neurons → rods and cones → back of eye
    b. rods and cones → bipolar neurons → ganglionic neurons → back of eye
    c. ganglionic neurons → rods and cones → bipolar neurons → back of eye
    d. ganglionic neurons → bipolar neurons → rods and cones → back of eye

15. Despite living in a visual society, people with impaired vision can function by taking advantage of _____.
    a. braille menus and buttons
    b. Seeing Eye animals
    c. cochlear implants
    d. Both A and B are correct.

THE PLANNER

Review your Chapter Planner on the chapter opener and check off your completed work.

9 Immunity and the Lymphatic System

WILEY PLUS Video

"Every time I travel, I get sick!" The health risks associated with travel fall into three categories. First, illness seems to follow stressful situations. Catching planes, arranging hotels, budgeting expenses, and dealing with cultural or language challenges cause anxiety. Anxiety lowers the body's resistance to infection. Second, travel offers exposure to new sights—and new diseases. When traveling, you are exposed to different bacteria and viruses than are found in your hometown. Your body has no experience fighting these new invaders, so often illness results. Finally, public transportation puts you in close proximity to other people. Airplane travel is a great way to cover long distances quickly, but you share that small space with others. Depending on the model of the plane, you may be traveling with anywhere from 104 to 550 people. Adding to the number of people on a single flight are those who flew in the plane previously. Surfaces are not sterilized between flights.

There are a few simple ways to reduce your risk of infection. Lower your stress by planning well in advance. Learn common phrases in the language of the country you are visiting. Ask your physician whether vaccines are recommended before entering your destination. Carry over-the-counter drugs, such as decongestants, that may reduce symptoms should they appear. Taking vitamin C, zinc, and echinacea may boost your immune system slightly.

The best way to enjoy your travel and prevent illness is simple. Wash your hands often and avoid touching your face.

CHAPTER OUTLINE

How Do We Adapt to Stress? 212

- The General Adaptation Syndrome Helps Overcome Stress
- Post-Traumatic Stress Disorder Is a Stress that Seems Never-Ending

Skin and Mucous Membranes Are the First Line of Defense 216

- Skin Is the Primary Physical Barrier
- Accessory Structures of the Skin Lubricate and Protect
- Hair—an Evolutionary Relic?
- Nails Reinforce the Fingers and Toes
- We Have Other Innate Physical Barriers
- Innate Chemical Barriers Can Also Defeat Pathogens

We Have a Second Line of Innate Defense 221

- Antimicrobial Proteins Are a Part of the Internal Innate Defense
- Fever Harms Pathogens Directly and Indirectly
- Inflammation Is Localized Fever
- Phagocytes Are Eating Cells

The Lymphatic System and Specific Immunity Are Our Third Line of Defense 224

- The Lymphatic System Reaches Most of the Body
- Lymphatic Capillaries and Vessels Resemble a Parallel Circulatory System
- Lymphatic Organs Filter and Protect
- Specific Immunity Relies on a Series of Deadly Cells that Recognize and Remember Pathogens

Immunity Can Be Acquired Actively or Passively 236

- Active Immunity Is the "Trainable" Immune System
- Passive Immunity Gets Help from the Outside
- In Autoimmune Diseases, Defense Becomes Offense

CHAPTER PLANNER

- ❑ Study the picture and read the opening story.
- ❑ Scan the Learning Objectives in each section:
  p. 212 ❑ p. 216 ❑ p. 221 ❑ p. 224 ❑ p. 236 ❑
- ❑ Read the text and study all figures and visuals. Answer any questions.

Analyze key features

- ❑ What a Scientist Sees, p. 215
- ❑ Process Diagram, p. 222 ❑ p. 231 ❑
- ❑ Health, Wellness, and Disease, p. 225
- ❑ Biological InSight, p. 226
- ❑ I Wonder..., p. 230
- ❑ Ethics and Issues, p. 235
- ❑ Stop: Answer the Concept Checks before you go on:
  p. 216 ❑ p. 221 ❑ p. 223 ❑ p. 234 ❑ p. 238 ❑

End of chapter

- ❑ Review the Summary and Key Terms.
- ❑ Answer the Critical and Creative Thinking Questions.
- ❑ Answer What is happening in this picture?
- ❑ Answer the Self-Test Questions.

9.1 How Do We Adapt to Stress?

LEARNING OBJECTIVES

1. **List** the innate defenses.
2. **Explain** specific and nonspecific immunity.
3. **Describe** the three phases of General Adaptation Syndrome.

Stress! It comes in many shapes and sizes, but scientifically, we define stress as any force that pushes the body out of optimum homeostatic conditions. Therefore, stress can arise from many situations that we do not normally consider stressful, such as digesting food, exercising, waking after a long sleep, or even walking outdoors after a few hours indoors. Indeed, if you think about it, the events that take place during daily living affect the body's internal chemistry, causing an imbalance, or stress, that must be corrected.

Technically, a "stressor" is any factor that causes stress. Some stressors are obvious. We've already seen the example of travel, and we know that having an infectious disease, ingesting a toxic chemical, or being exposed to winter storms also stresses the body. If the original stress resulted from moving to a cold area, you might generate heat by shivering. If the stressor is an increase in blood sugar caused by eating an ice cream sundae, the pancreas will secrete insulin to reduce blood sugar levels. Other stressors—conforming to social expectations, for example—are less obvious. Have you felt uneasy while trapped in a painfully slow checkout line? Did you fantasize pushing to the head of the line or loudly urging the cashier to "speed it up"? School tests and grades are another familiar source of stress. How many students show signs of suffering that particular stress on college campuses during finals week?

Invasions of fungal, bacterial, or viral **pathogens** are a very important category of stressors. A pathogen is any agent that can cause disease. To a pathogenic bacterium, humans are a walking meal of proteins, sugars, fats, and other good things to eat. To a virus, we are an uncountable number of cells that can be converted into "factories" for making thousands of new viruses. Despite the huge array of pathogens waiting to infect us, most of us are healthy, most of the time. That is because we have a very sophisticated defensive and counterattacking system in our bodies—the immune system.

pathogen Agent that produces disease.

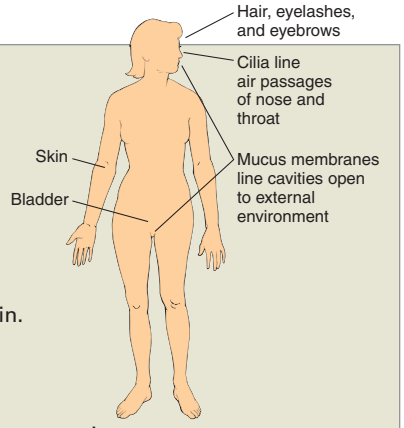
Our immune system is really three lines of defense: two we are born with, and one we acquire throughout our lives. Our inborn ability to defend against pathogens is called **innate immunity**, or **nonspecific immunity**. The most obvious of our innate defenses is our outer layer of epithelium—the **cutaneous** membrane or the skin, which along with mucous membranes is often called our first line of defense. Our second line of defense, also present from birth, is a set of general internal pathogen-fighting measures: antimicrobial proteins like **interferon**, fever, inflammation, and "eating cells" called **phagocytes**. These innate defenses are equally active regardless of whether the threat is a bacterial invasion in the moist environment of your throat or a long wait in line, as in Figure 9.1. Whatever the stress is, these nonspecific, innate defenses will respond the only way they can, repeating the same

interferon A protein produced by virally infected cells that helps other cells respond to viral infection.

phagocytes Cells that endocytose (engulf) pathogens.

A typical stressful situation common in today's world • Figure 9.1

Innate defenses Table 9.1



Component	Functions
First Line of Defense: Skin and Mucous Membranes	
Physical Factors	
Epidermis of skin	Forms a physical barrier to the entrance of microbes.
Mucous membranes	Inhibit the entrance of many microbes, but not as well as intact skin.
Mucus	Traps microbes in respiratory and gastrointestinal tracts.
Hairs	Filter out microbes and dust in nose.
Cilia	Together with mucus, trap and remove microbes and dust from upper respiratory tract.
Lacrimal apparatus (tears)	Dilutes and washes away irritating substances and microbes.
Saliva	Washes microbes from surfaces of teeth and mucous membranes of mouth.
Urine	Washes microbes from urethra.
Defecation and vomiting	Expel microbes from body.
Chemical Factors	
Sebum	Forms a protective acidic film over the skin surface that inhibits growth of many microbes.
Lysozyme	Acts as antimicrobial substance in perspiration, tears, saliva, nasal secretions, and tissue fluids.
Gastric juice	Destroys bacteria and most toxins in stomach.
Vaginal secretions	Discourage bacterial growth by being slightly acidic; flush microbes out of vagina.
Second Line of Defense: Internal Defenses	
Antimicrobial Proteins	
Interferons (IFNs)	Protect uninfected host cells from viral infection.
Complement system	Causes bursting of microbes, promotes phagocytosis, and contributes to inflammation.
Natural killer (NK) cells	Kill infected target cells by releasing granules that contain perforin. Phagocytes then kill the released microbes.
Phagocytes	Ingest foreign particulate matter.
Inflammation	Confines and destroys microbes and initiates tissue repair.
Fever	Intensifies the effects of interferons, inhibits growth of some microbes, and speeds up body reactions that aid repair.

defense each time. See **Table 9.1** for a summary of the innate defenses.

If these defenses fail to ward off the threat, our third line of defense and counterattack comes into play. It is called **specific immunity** because it attempts to eradicate that specific invader. The mechanisms of specific immunity, including the interactions of white blood cells, antibodies, and macrophages, are discussed later in this chapter.

All stressors place physiological demands on the body, which can cause cells to halt routine activities and instead respond to the immediate demands of that stressor. The physiological changes associated with stress may alter sleep patterns or even personality. Regardless of the stressor, however, the body's response follows a general pattern: opposing the stressor, accommodating to it, and finally succumbing to it. This pattern, called the General Adaptation Syndrome, is described next.

The General Adaptation Syndrome Helps Overcome Stress

You may have heard that "fight or flight" is a common response to danger. Fight or flight is one of our innate, automatic physiologic responses to stress, and in fact is the first of the three stages of General Adaptation Syndrome, or GAS. This series of predictable responses to stress is an attempt to adapt and deal

with the original stressor. The three stages of this reaction are: (1) alarm, (2) resistance, and (3) exhaustion, as shown in Figure 9.2. During the alarm stage, we feel that sudden rush of adrenaline, that immediate jolt of energy that provides the speed, power, and quickness of wit to remove ourselves from danger. The alarm stage is initiated by the autonomic nervous system. If this fight-or-flight response fails to overcome the stress, however, the body continues working through the other stages of GAS: resistance and exhaustion.

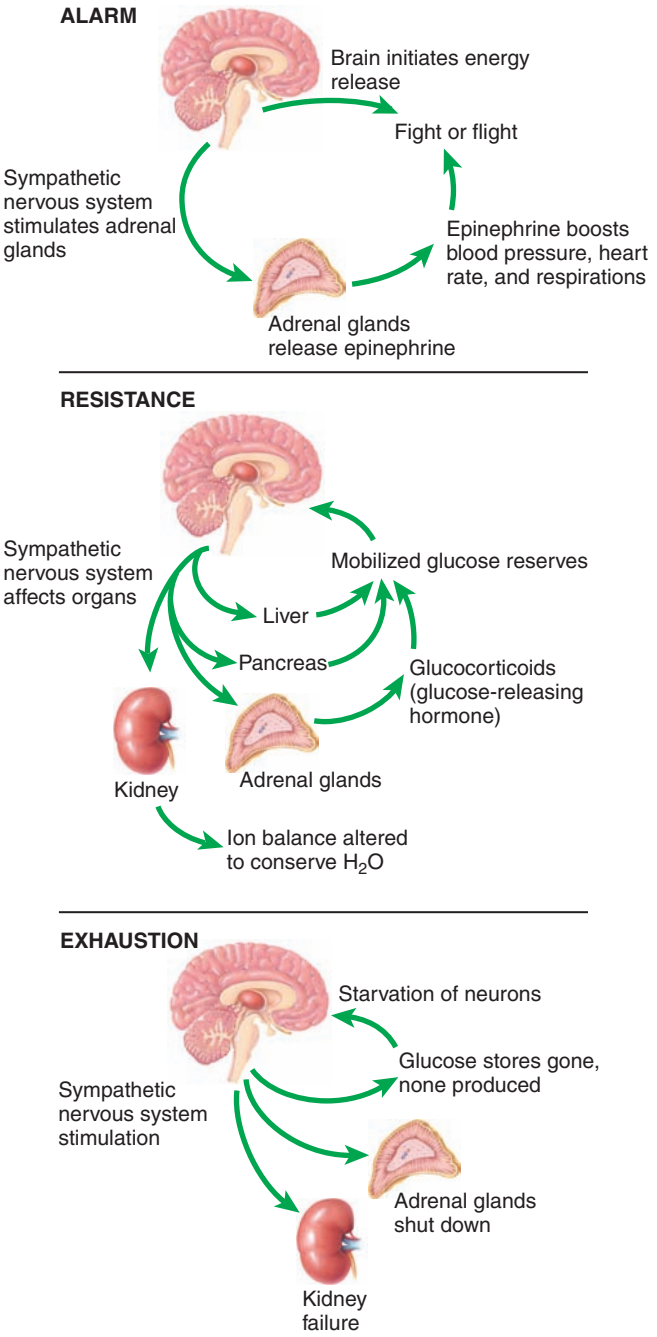
During the alarm phase, we may flee or fight.

The alarm phase occurs when the individual detects danger, and the body first starts to deal with it. Alarm is characterized by immediate, almost frenetic, action. The fight-or-flight nervous system (also called the sympathetic division of the autonomic nervous system) takes over, and the body jumps into action. Energy reserves are mobilized, blood sugar increases sharply, and the body prepares to defend itself or flee. The alarm phase is controlled by the release of the hormone **epinephrine**, also known as adrenaline. This is the hormone responsible for our feelings of fear and for "adrenaline rushes." Epinephrine boosts blood pressure, heart rate, and respiratory rate, all of which speed the delivery of highly oxygenated blood to the skeletal muscles. Sweat production also increases, resulting in what is often called a "cold sweat."

epinephrine A hormone released from the adrenal gland in response to stress.

In sports, the nervous state before competition shows the alarm phase in action: You experience heightened mental alertness, and increased energy becomes available to the skeletal muscles as energy stored in glycogen and lipids is released. The circulatory system shunts blood to the organs needed for fighting or fleeing, mainly moving blood toward the skeletal muscles and away from the skin, kidneys, and digestive organs. Your body, after all, is acting as if your life depends on leaving the situation—or fighting your way out of it—with maximum haste. To save your life, is it more important to digest your last meal or to prime your skeletal muscles for action? (After all, if you run too slowly when being chased by a tiger, that last meal may literally be your last meal.) Shifting the blood flow away from the digestive organs will often produce "butterflies" in the stomach.

Although other hormones may be involved in the alarm phase, especially if the stressor is causing blood loss, epinephrine is the key hormone at this point. The changes effected during the alarm phase will help the body operate at peak performance while confronting or avoiding a stressor; however, these changes are less appropriate as responses to social stresses. Increasing heart rate and blood glucose will not speed up a checkout line, but they will boost your frustration level. We call a severe and inappropriate triggering of the alarm phase a "panic attack." For more about this, see *What a Scientist Sees: Marriage May Often Cause a Momentary Feeling of Panic*.



Three stages of GAS • Figure 9.2

The General Adaptation Syndrome (GAS) has three phases, increasing in severity from alarm to resistance and finally exhaustion.

WILEY PLUS Video

WHAT A SCIENTIST SEES

NATIONAL GEOGRAPHIC

Marriage May Often Cause a Momentary Feeling of Panic

Occasionally, a person may experience episodes of free-floating panic, with a racing heart, profuse sweating, and an inexplicable feeling of dizziness and nausea. These symptoms are characteristic of panic disorder, a chronic state characterized by panic attacks that often occur during times of prolonged stress or life-changing steps, such as during pregnancy or before marriage or graduation. Unfortunately, these physiological responses are inappropriate for the situation, and often do little more than foster more panic. That is not a welcome response to the festivities surrounding the wedding day and night.

Think Critically

1. What is the main organ of the body responsible for the initial panic feelings associated with life-changing events?
2. What sort of events or situations might trigger a panic attack in an otherwise healthy person?
3. Knowing this, can you prescribe some techniques that might help alleviate this feeling should you ever begin to experience a panic attack?

The resistance phase is a response to prolonged stress. During the resistance phase, the body concentrates on surviving the stress rather than evading it. The individual is likely to feel tired, irritable, and emotionally fragile. He or she may overreact to simple daily irritants or commonplace events. During the resistance phase, the brain consumes immense amounts of glucose that it obtains from the blood. A series of hormones ensure that lipid and protein reserves are continuously tapped to maintain the high blood sugar level needed by the brain.

The skeletal muscles become more concerned with survival than with rapid movement, and they begin to break down proteins. The breakdown of lipids sustains the high fuel supply even during starvation, as the liver begins converting stored carbohydrates into glucose.

In addition, blood volume is conserved by maintaining water and sodium in the body, which unfortunately simultaneously raises blood pressure. Potassium and hydrogen ions are lost at abnormally high rates. Some of the hormones responsible for maintaining the resistance phase inhibit wound healing, so wounds may become infected before they heal, adding to the overall stress on the body.

The resistance phase lasts until the stress is removed, lipid reserves are depleted, or complications arise from the altered body chemistry. Poor nutrition, physical damage to the heart, liver, or kidneys, or even emotional trauma can abruptly end the resistance phase.

The exhaustion phase can be terminal. Resistance requires us to maintain extreme physiological conditions, and prolonged resistance can lead to the exhaustion phase, which is a polite way of saying, "death through organ failure and system shutdown." During exhaustion, homeostasis breaks down through the depletion of lipid reserves and the loss of normal blood electrolyte balance. Accumulated damage to vital organs may cause the affected organ systems to collapse. Mineral imbalances, due to sodium retention and potassium loss, may cause neurons to fail and thus result in the failure of skeletal and cardiac muscle.

Post-Traumatic Stress Disorder Is a Stress that Seems Never-Ending

After severe stress, such as witnessing or being victimized by warfare, rape, or violent crime, some people develop post-traumatic stress disorder (PTSD). This disorder is a type of stress reaction that may get worse, not better, with time. Biologically, PTSD looks like a prolonged resistance

phase of GAS. In addition, research has shown that victims of PTSD show abnormal brain patterns and changes in the volume of certain areas of the brain. The amygdala, a center associated with emotion and fear, and the hypothalamus, the homeostasis center, are most often affected. These changes help explain the symptoms of PTSD: fear, heightened vigilance, panic reactions, inability to concentrate, and memory disorders. PTSD can usually be treated with psychotherapy or psychoactive drugs.

CONCEPT CHECK STOP

1. **What** are the innate defenses?
2. **What** are the defining characteristics of specific and nonspecific immunity?
3. **What** are the three phases of General Adaption Syndrome and **what** happens during each phase?

9.2 Skin and Mucous Membranes Are the First Line of Defense

LEARNING OBJECTIVES

1. **Describe** the structure and functions of the skin.
2. **List** the functions of the accessory structures of the skin.
3. **Explore** the role of the skin and accessory structures in innate defense.

We can think of GAS as a set of behavioral defenses—activities that the body undertakes to cope with prolonged stresses. In addition, the body has other innate, or inborn, defenses. The most obvious of these is our skin. This outer layer of epithelium is a **cutaneous** membrane that is often called our first line of defense. The skin is our first line of defense against pathogenic invasions, but **mucous membranes** also serve as physical barriers against invasion.

A membrane is a simple organ composed of a layer of simple or stratified epithelium supported by connective tissue. A mucous membrane lines any cavity open to the exterior, including the mouth, digestive, respiratory, urinary, and reproductive tracts. The skin and mucous membranes are physical barriers. Other forms of innate immunity, including chemical deterrents and general antipathogen measures, will be discussed later in this section.

Skin Is the Primary Physical Barrier

The skin is the largest organ of the human body. It encases the body, protecting it from desiccation (drying out) and preventing the entry of disease-causing microbes. Sensory receptors in the skin monitor the immediate environment, noting light touch, heavier pressure, and temperature. The skin also has vital homeostatic functions, such as helping the body regulate water content and temperature. Finally, the skin produces vitamin D, which is necessary for bone growth and development. The skin is composed of a superficial **epidermis** and a deeper **dermis**, as shown in **Figure 9.3**.

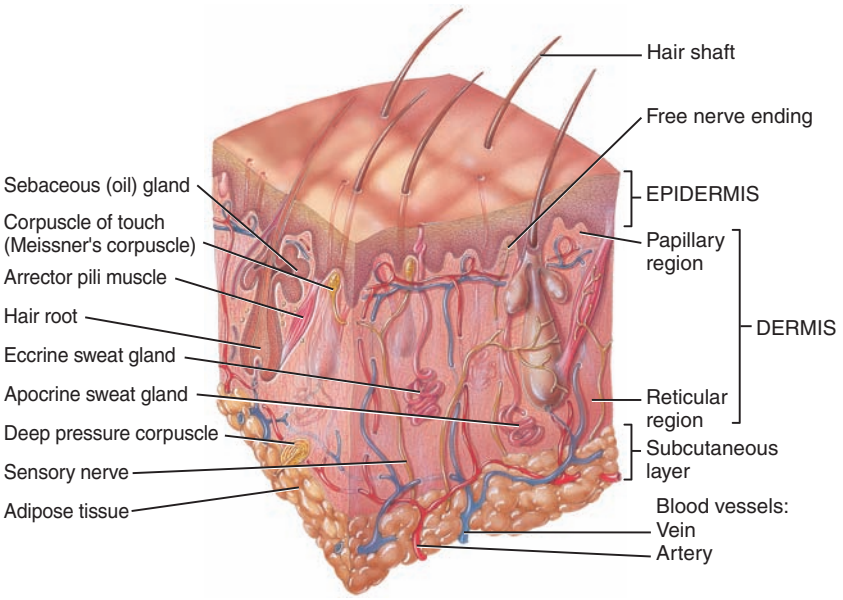
epidermis The outermost, nonvascular layer of the skin.

dermis The underlying, vascularized, connective tissue layer of the skin.

The epidermis is composed of stratified squamous epithelium, but most of the cells are dead. These squamous cells are produced deep within the tissue, in a layer immediately above the dermis. As these cells divide, they continually push the daughter cells upward, away from the nutrient source in the dermis. Because epithelium has no blood supply, the epithelial cells are nourished by capillaries in the upper dermis. As the epidermal cells are pushed away from these capillaries, the cells weaken and die. This gradual dying process changes the appearance of the cells, resulting in visible layers in the epidermis.

The top layer of the epidermis is composed of dead cells joined by strong cell-to-cell junctions. The cells are filled with **keratin**, a waterproof substance that accumu-

Components of the skin • Figure 9.3



Sectional view of skin and subcutaneous layer

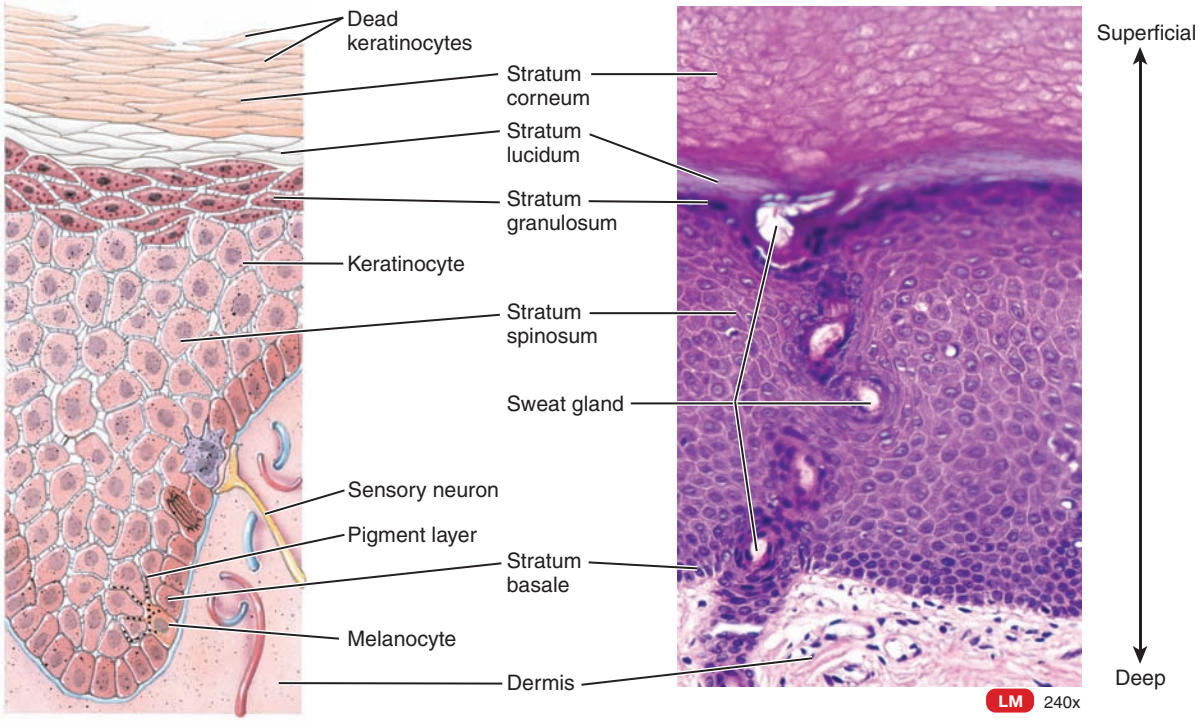
lates in the epidermal cells as they progress toward the skin surface. Because of the quantity of keratin held within these cells, they are called **keratinocytes**. This layer of dead keratinocytes provides the skin's nonspecific defense against invasive pathogens. Few pathogens are attracted to dead cells, and keratin repels waterborne pathogens along with water.

Skin color results from the brown pigment **melanin**, which is produced by **melanocytes** in the deepest epidermis, as shown in **Figure 9.4**. UV light stimulates production of a hormone that in turn stimulates the melanocytes to produce more melanin, resulting in a tan. Interestingly, humans, regardless of race, have the same number of melanocytes; different levels of melanin production account for our different skin colors. Melanocytes are less active in people with pale skin. In those with dark skin, highly active melanocytes produce lots of melanin, even with low sunlight exposure. In evolutionary terms, dark skin is an adaptation that protects tropical people from the intense sun. White skin is adaptive closer to the Poles because it allows the entry of enough ultraviolet light to produce vitamin D. Skin cancer is a concern for anyone who has exposed their skin to sunlight.

melanocytes Cells that produce melanin, a brown, light-absorbing pigment.

Skin cancer occurs in the epidermis. Skin cancer is common in the United States. In 2004, 1 in 65 Americans was diagnosed with some form of skin cancer. The good news is that skin cancer occurs in the obviously

Pigmented epidermis • Figure 9.4



Photomicrograph of a portion of the skin

visible epidermal cells and is easily detected at an early stage. As with all cancers, these tumor cells eventually begin to multiply rapidly and uncontrollably. Skin cancer is related to sun exposure because the ultraviolet radiation in sunlight damages the DNA in skin cells.

Basal cell carcinoma (BCC) is the most common cancer in humans, accounting for over 1 million cases per year in the United States alone. This cancer develops in the basal or deepest cells of the epidermis, usually in places that are routinely exposed to the sun. The appearance can vary, but the tumor is usually a slow-growing, shiny or scaly bump. A wound that repeatedly heals and opens may be a form of BCC. These cancers rarely metastasize, or spread to other tissues, but dermatologists still recommend that they be removed.

Squamous cell carcinoma (SCC) is a tumor of the upper layers of the skin. These cancers usually develop a crusty or scaly covering and grow rapidly. The threat of metastasis is much higher with SCC than with basal cell carcinoma, so SCC tumors should be removed as soon as possible. Approximately 16% of skin cancer cases are SCC.

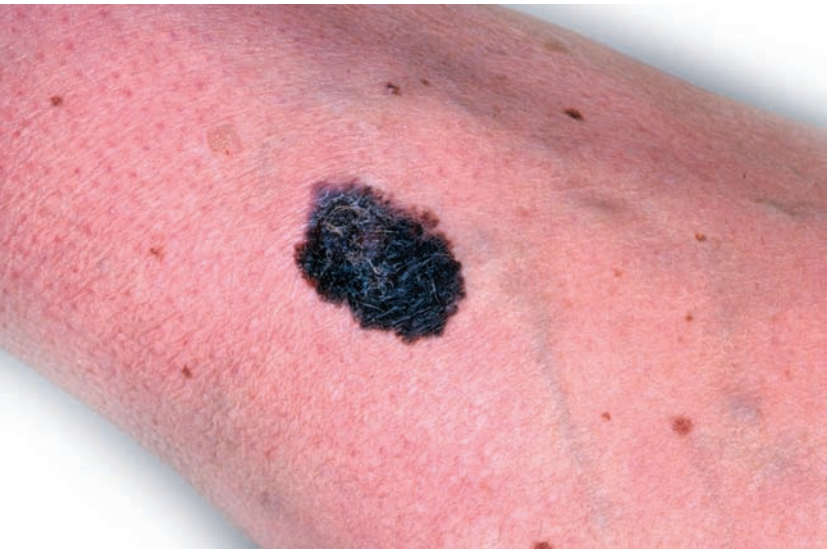
Melanomas (Figure 9.5) are the most aggressive skin cancer, rapidly spreading to the lymph nodes and other tissues, but luckily they comprise only 4% of all diagnosed skin cancers. The cancerous cells are melanocytes—ironically, the same cells that protect us from harmful UV radiation. Cancerous melanocytes divide rapidly and spread to the dermis.

The dermis is the source of nutrition for the epidermal cells. The bottom layer of skin, the dermis, is composed of loose, irregular connective tissue. The dermis has a large blood supply and extensive innervation. The **accessory organs** of the skin (hair, glands, and nails) lie in the dermis, as do all of the sensory organs of the skin. Free (exposed) nerve endings register the sensation of pain (**nociceptors**), whereas specialized structures attached to cutaneous nerves respond to light touch and pressure. When you put on a shoe in the morning, corpuscles in the skin of your foot register the shoe's pressure. During the day, the pressure from that shoe doesn't change, and you are no longer aware of the presence of your shoes. Should the pressure become painful, however, pain receptors remind you of your shoes. Unfortunately, pain receptors do not adapt, so your discomfort will remain until you somehow remove the excess pressure.

nociceptors
Nonadapting pain receptors in the skin (*noci* = pain).

Melanoma • Figure 9.5

Melanomas most often occur in individuals who have been subjected to excessive hours of bright sunlight. Melanomas grow rapidly, include varying shades of brown, and often have indistinguishable borders.



Accessory Structures of the Skin Lubricate and Protect

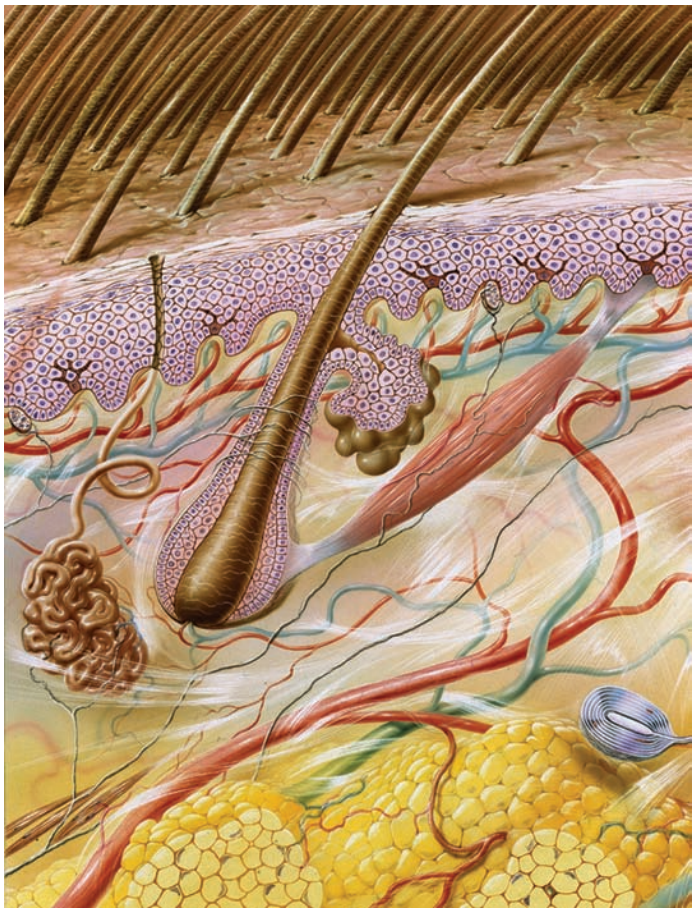
The accessory structures of the skin are the glands, hair, and nails. The glands produce sweat for thermal homeostasis or oils to keep the skin flexible. The hair and nails are protective structures.

Oil (**sebaceous**) glands are found within hair follicles. Oil is secreted onto the hair shaft, helping to keep the hair and surrounding skin supple. The hormones of puberty increase the output of these glands, often leading to acne, defined as a physical change in the skin because of a bacterial infection in the sebaceous glands. Acne causes the development of lesions, cysts, blackheads, or whiteheads, common terms for various combinations of dirt, infection, and skin oils. Fortunately, doctors can now treat virtually all types of acne and usually prevent scarring that can follow uncontrolled infections.

Sebaceous glands are located wherever there is hair, as shown in Figure 9.6. This means we have oil glands everywhere on our bodies except in hairless skin, such as

Sebaceous gland • Figure 9.6

These glands are always associated with hairs, lying next to the hair with their ducts opening directly onto the hair (colored purple in this figure to match the epidermal cells from which they originate). When the hair is moved, oils are secreted from these ducts.



on the lips. The absence of oil glands explains the need for lip balms to alleviate drying and chapping in this oil-less skin.

The skin plays a crucial role in temperature control. Sweat glands are active in maintaining thermal homeostasis (see **Figure 9.7**). They are found all over the body, with the exception of the lips and the tip of the penis. Sweat glands are basically a tube from the surface of the skin into the dermis. At the base of the dermis, the tube coils into a knot. Most sweat glands open to the surface at a pore, with no hair associated. The larger sweat glands of the axillary region, the **groin** region, and the areolae of the breasts become active during puberty.

Sweat is produced in response to rising internal temperature. Blood vessels in the dermis dilate, allowing a larger volume of blood to flow from the core of the body to the skin. This blood transports excess heat to the skin, where it activates thermoreceptors that send impulses to the brain to activate the sweat glands. The blood, having transferred its heat to the skin, returns to the heart somewhat cooler than it was previously.

During average activity, your sweat glands produce approximately a coffee cup (150 ml) of fluid per day. Athletic activity increases this volume tremendously; up to 2.5 liters of fluid per hour can be lost during strenuous activity in hot weather. In the Tour de France, Lance Armstrong once lost a full 6% of his body weight during a hot, intense, one-hour race. This extreme fluid loss took a toll on his performance and overall health, and Armstrong needed two days to recover. For optimal performance and general health, endurance athletes must hydrate before and during competition.

Hair—an Evolutionary Relic?

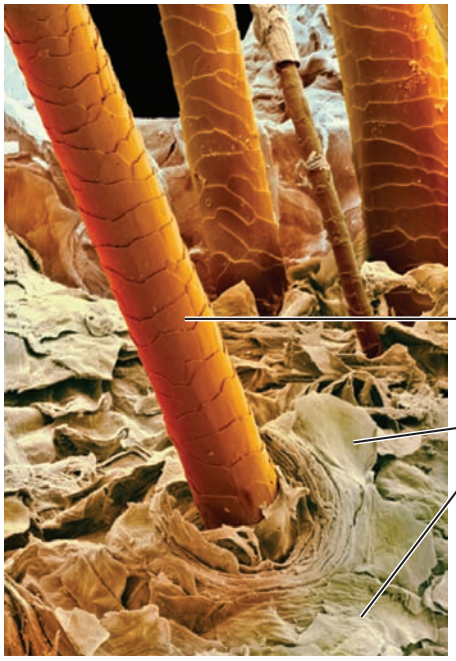
What is hair, and why does it grow where it does? Although we think of hair mainly as the coarse structures projecting from and protecting our head, hair actually covers most of our bodies, including our face, shoulders,

Functioning sweat glands • Figure 9.7

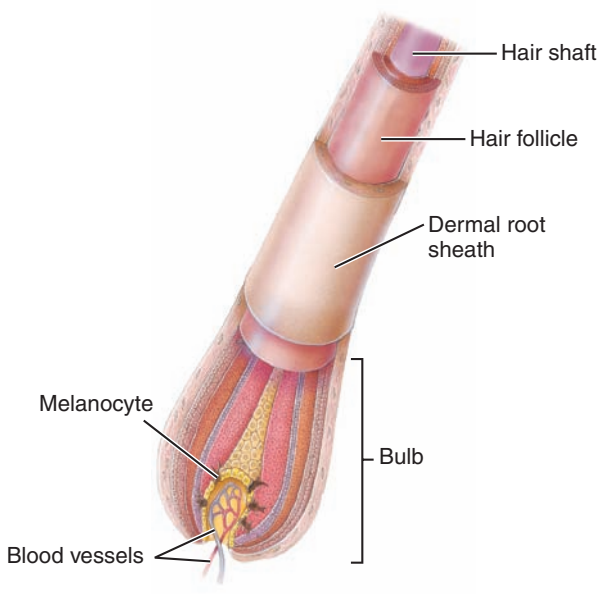
Thermal homeostasis is regulated in part by the skin. Sweat, produced from sweat glands all over the body, is secreted onto the surface of the skin, where it evaporates. The process of evaporation removes a large amount of heat from the surface of the body.

Hair • Figure 9.8

Hair is formed from pockets of epithelium that dive deep into the dermis. The hair follicle produces a hair shaft, composed of epithelial cells arranged in many layers. The innermost layer of the hair shaft contains the pigments that color our hair. The bulb of the hair follicle is what keeps the cells that form the hair shaft alive. Decreasing the blood flow through the bulb results in losing the hair shaft.



Several hair shafts showing the shingle-like cuticle cells



back, and belly. Humans are not really "hairless apes," although most of our hair is fine and sparse compared to that of the other apes. Hair serves as an insulator as well as protection for the eyes, nostrils, and ear openings. On our heads, hair prevents loss of heat from blood flowing beneath the scalp. On a man's face, hair indicates sexual maturity.

Hair is formed from the division of specialized epidermal cells in the hair **follicle**, located in the dermis. See **Figure 9.8**. Just as new epidermal cells push older cells outward, the growing hair shaft pushes older cells away from the blood supply. Beyond the epidermis, the hair shaft is composed of dead cells.

follicle A small cavity or cul-de-sac; hair originates in a hair follicle.

Nails Reinforce the Fingers and Toes

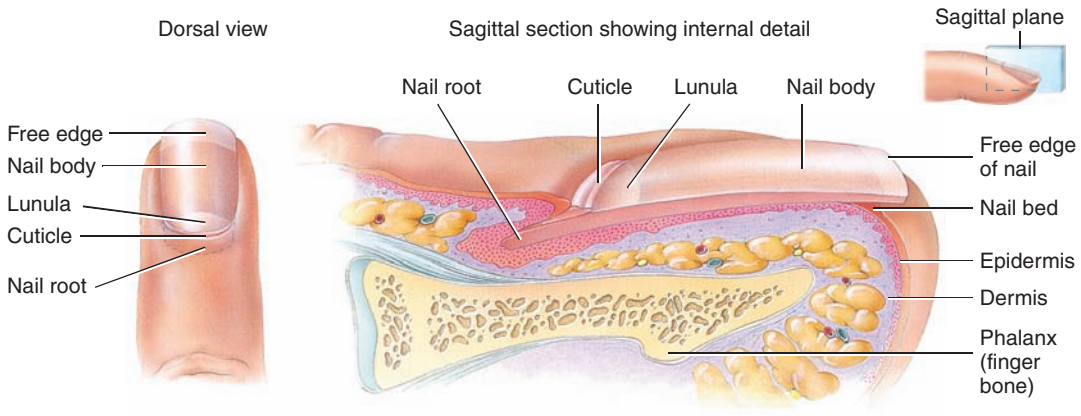
Nails are flattened sheets of **keratinized** cells that protect the ends of the digits, as shown in **Figure 9.9**. Nails arise from a thick layer of specialized epithelial cells at the nail root called the **lunula**, located at the base of the nail bed. The **cuticle** is a layer of epidermis that covers the base of the nail. Nails protect the ends of the digits from physical damage as we wave them through the environment (Figure 9.9).

keratinized Filled with keratin and therefore waxy.

We Have Other Innate Physical Barriers

Like the cutaneous membrane, mucous membranes provide nonspecific immunity. This immunity is essential, because mucous membranes line any cavity open to the exterior, including the mouth and digestive tract, the respiratory tract, the urinary tract, and the reproductive tract. Instead of being covered in keratinized dead cells, these tracts are covered in mucus that retards pathogens. The mucus, secreted by the epithelial cells of the membrane, constantly washes the membrane. Often, larger volumes of fluid wash these membranes as well. Urine flows across the urinary tract membrane; vaginal secretions flow out of the body across the mucous membranes of the female reproductive tract; and saliva continuously washes the oral cavity. These "barriers" are among the chemicals that supplement the physical barriers.

Nails • Figure 9.9



Innate Chemical Barriers Can Also Defeat Pathogens

When the physical innate barriers fail to stop a pathogen, we have another component to the first line of defense: chemical barriers. **Sebum** forms a protective acidic film over the skin surface that is hostile to many bacteria. Perspiration, tears, and saliva contain an enzyme called **lysozyme**, which is a natural antibacterial chemical. The extremely low pH of the stomach (approximately pH 2) is a function of the **gastric juices**. These fluids, produced by the stomach lining, create an unfriendly environment for many pathogens.

We also have many strains of harmless bacteria that help create a hostile environment for other microbes: for example, the *Lactobacillus* bacteria in the vagina helps lower pH levels, which in turn kills off certain fungi and bacteria.

CONCEPT CHECK STOP

1. **How** does the structure of skin allow it to function as an innate defense mechanism?
2. **What** is the function of sebaceous glands? Sweat glands?
3. **How** do nails and hairs provide protection to the body?

9.3 We Have a Second Line of Innate Defense

LEARNING OBJECTIVES

1. **Compare** the complement system and interferon.
2. **Relate** fever and inflammation to feelings of fatigue during illness.
3. **Describe** the role of phagocytes.

Despite the "fortress wall" of skin, mucous membranes, and chemical barriers, bacteria and other pathogens can often enter the body and cause homeostatic imbalances. When this happens, we have a second line of nonspecific defense—internal innate defenses. As with the first line of defense, these innate defenses still destroy pathogens without distinguishing between—or even recognizing—them. That is why we label them nonspecific. These nonspecific internal innate defenses include protective or antimicrobial proteins, fever, inflammation, and phagocytes.

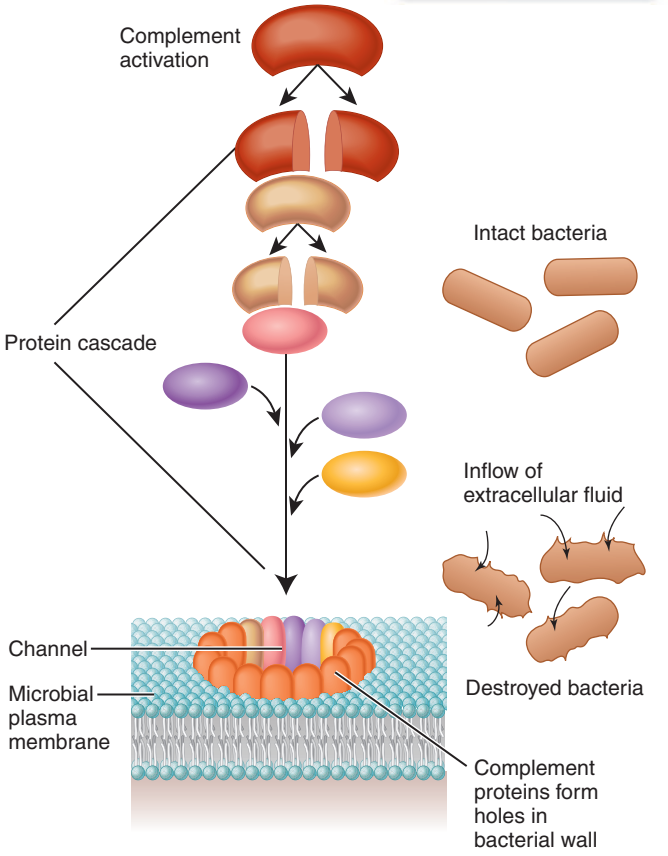
PROCESS DIAGRAM

THE PLANNER

The complement system: One innate internal defense against bacterial invasion • Figure 9.10

When bacteria are discovered in the body, the complement cascade is activated. These free-floating plasma proteins are brought together to form structures that pierce the bacterial wall, destroying it.

WILEY PLUS Interactivity



Antimicrobial Proteins Are a Part of the Internal Innate Defense

One nonspecific internal defense against bacteria is called the **complement system**, as shown in Figure 9.10. This series of chemical reactions brings together a group of proteins that are usually floating freely in the plasma. These proteins are stacked in a specific order to create a "complement" of proteins that functions like an antibacterial missile. When a bacterial invasion is encountered, the complement complex assembles, attaches to the bacterial walls, and impales the cell with the protein complex. With the bacterial wall breached, osmotic pressure forces water into the bacterium, destroying its chemistry and killing it.

The complement system is effective against bacteria but not viruses. When cells are infected with a virus, another defensive protein response is needed. The chemical answer to viral infection is **interferon**, as shown in Figure 9.11. Interferon is a "local" hormone that is secreted to affect nearby cells. It is a chemical warning, similar to the tornado warning sirens of the Midwest or the tsunami warnings in coastal communities. When cells detect interferon in the extracellular fluid, they prepare for viral invasion. Ideally, the viral infection can then be limited to a small area, allowing it to run its course with little effect on overall body functioning.

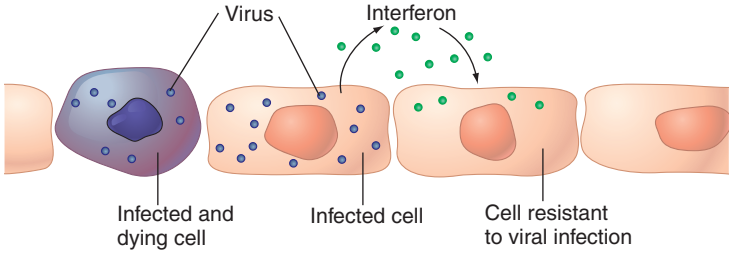
Fever Harms Pathogens Directly and Indirectly

Fever is defined as a change in the body's temperature set point, resulting in an elevation in basal body temperature above 37.0°C (98.6°F). Proteins called **pyrogens** reset the body's thermostat to a higher temperature. Fever may harm the pathogen directly, but more likely it aids defensive mechanisms by raising the metabolic rate. For every 1°C rise in body temperature, your metabolic rate increases by 10%. At elevated temperatures, enzymes and repair processes work faster, cells move more quickly, and specific immune cells are mobilized more rapidly. In addition, your spleen **sequesters** (holds) more iron at higher temperatures, which many bacteria require to reproduce.

The adage "feed a fever" is correct. Fever elevates your basal metabolic rate, increasing your use of energy. Unless you replenish your energy supplies, you will tire quickly, which will increase the homeostatic imbalance

Interferon fights viral invasion • Figure 9.11

Cells produce interferon to help ward off a viral infection.



created by the pathogen. Feeding your body will aid the recovery process by providing nutrients necessary for the functioning of the immune cells, whereas not eating may deplete your reserves and give the pathogen the upper hand.

Inflammation Is Localized Fever

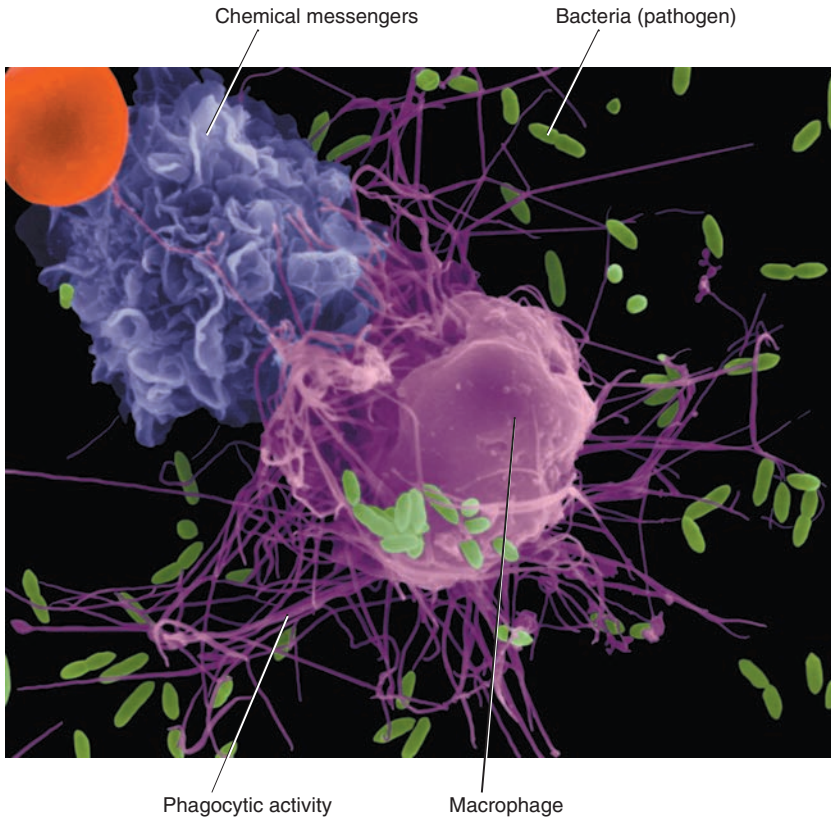
Inflammation is similar to fever in its goal, but it is a localized, not whole-body, method for increasing enzyme function. **In situ** (in place) swelling, redness, heat, and pain are associated with inflammation. Damaged or irritated cells release **prostaglandins**, proteins, and potassium, which trigger inflammation when released into the interstitial fluid. The benefits of inflammation include temporary tissue repair, blockage of continued pathogen entry, slowing of pathogen spreading, and quicker repair of the damaged tissue. The redness associated with inflammation of the skin shows how capillaries become "leaky," allowing blood to bring immune-system cells and various compounds to injured or diseased tissues.

Inflammation can be triggered by many factors, including pathogen entry, tissue abrasion, chemical irritation, or even extreme temperature. For example, mosquito bites stimulate inflammation in almost everyone. The red, hot, itchy welt actually represents a local inflammation resulting from the lady mosquito's poor table manners. As she completes her meal and withdraws her proboscis, she spits into the skin, releasing cellular debris and salivary chemicals that initiate an inflammatory response.

Phagocytes Are Eating Cells

Phagocytes are a final nonspecific defense for dealing with stressors. The root *phago* means "to eat"; and you already know that *cyte* translates to "cell." Phagocytes, therefore, are eating cells, or cells that wander through the tissues, engulfing and removing anything that does not belong there. Phagocytes, the first cellular line of defense against pathogens, remove all dead or dying cells, cellular debris, and foreign material. This "clean sweep" action classifies them as a nonspecific defense.

Phagocytes come in different sizes. **Microphages** are quite small and are mainly found in the nervous system. **Macrophages** are large, actively patrolling cells. They arise from blood cells and travel through every tissue looking for foreign material—see **Figure 9.12**. Some tissues have resident, or "fixed," macrophages, whereas other tissues get patrols of wandering macrophages passing through, like security guards making the rounds at a mall.



Macrophage eating technique • Figure 9.12

Both microphages and macrophages are attracted to pathogens and damaged cells via chemical messengers. Once they locate a pathogen or damaged cell, they surround, engulf, and destroy it. Some phagocytes are capable of continuous removal of pathogens and cellular debris, whereas others have a limit on how much they can ingest. Once they reach that limit, the phagocytes die and must be removed. Pus is actually dead phagocytes, filled with cellular debris from the wound they were helping to clean.

CONCEPT CHECK

STOP

1. **How** do the complement system and interferon work?
2. **Why** do fever and inflammation contribute to feelings of fatigue during illness?
3. **How** do phagocytes assist in disease prevention?

9.4 The Lymphatic System and Specific Immunity Are Our Third Line of Defense

LEARNING OBJECTIVES

1. **Relate** the structures of the lymphatic system to their functions.
2. **Compare** the lymphatic vessels to the blood vessels.
3. **List** the steps involved in cellular and humoral immunity.
4. **Discuss** the functions of the cells of the immune system.

When nonspecific defenses, such as those discussed earlier in the chapter, prove inadequate, our body can employ more selective defenses against disease. This third line of defense, called our acquired or specific **immune response**, is governed by the **lymphatic system**. The immune response is acquired, not innate, meaning that it is a conditioned or "learned" reaction of the lymphatic system. Whereas the innate defenses function the same way regardless of the pathogen, the acquired immune response is specific. Each pathogen triggers a slightly different reaction, and the immune system must "learn" to identify each pathogen through experience.

immune response
The disease-fighting activity of an organism's immune system.

lymphatic system
The tissues, vessels, and organs that produce, transport, and store cells that fight infection.

The lymphatic system helps explain why we rarely need medical help to combat infectious disease and how we benefit from vaccinations. The lymphatic system is complicated but lovable. Without its good offices, you likely would not be studying human biology today. Instead, you would be long gone. See *Health, Wellness, and Disease: Mononucleosis and the Spleen* to read about how that disease affects the largest organ of the lymphatic system—the spleen.

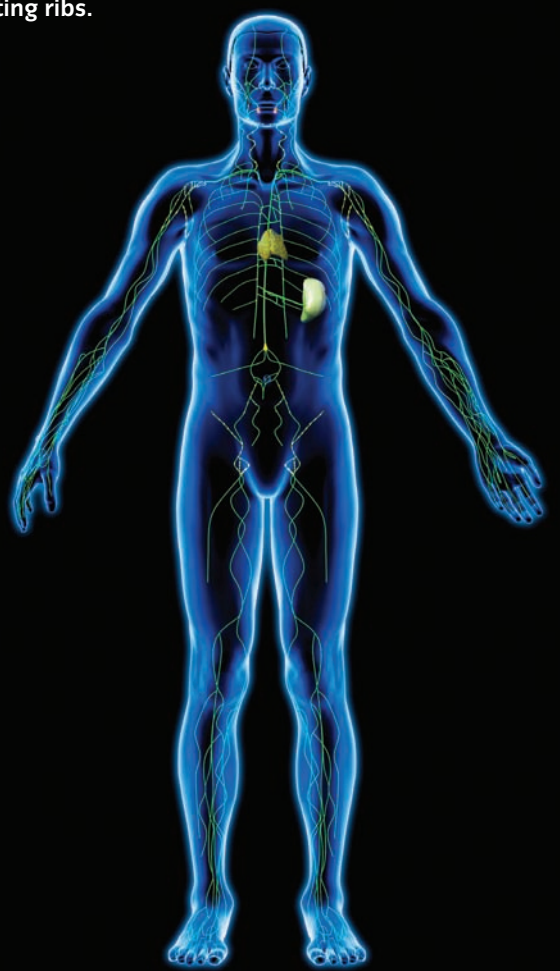
The Lymphatic System Reaches Most of the Body

The lymphatic system is composed of lymph, lymphatic vessels, and lymphatic organs and tissues. The organs of the lymphatic system include the tonsils, spleen, thymus, lymph nodes, and the Peyer's patch glands of the digestive system. Connecting these organs is a network of lymphatic vessels that collect lymph from the tissues and deposit it in the bloodstream.

Like the circulatory system, the lymphatic system touches most of the body and carries out both transportation and homeostatic services. You are probably familiar with the lymph nodes, those small, bean-shaped structures that you may feel alongside your Adam's apple when you have a sore throat. You may be surprised to learn that you have lymph nodes elsewhere, including your intestinal tract and chest. These lymph nodes function in concert with lymphatic tissue, organs, and vessels to (1) return excess fluid from the tissues to the bloodstream, (2) absorb fats from the intestine and transport them to the bloodstream, and (3) defend the body against specific invaders (see **Figure 9.13**).

The lymphatic system • Figure 9.13

Note the yellow thymus in the center of the thoracic cavity and the spleen off toward the left, beneath the floating ribs.



HEALTH, WELLNESS, AND DISEASE

Mononucleosis and the Spleen

The organs of the lymphatic system are rarely discussed. A sore throat often leads to a mention of swollen lymph glands, but the rest of the lymphatic organs remain relatively obscure in our daily life. The largest lymphatic organ is the spleen, and yet this organ hardly ever warrants attention. The spleen lies on the left side of the body, in the left lumbar region. It is approximately 5 inches by 3 inches across, and is composed of loosely aggregated red and white pulp that give it a soft consistency. There is a capsule surrounding the spleen, helping to maintain its shape. Recently it was discovered that the spleen is composed of two or three distinct lobes. The function of the spleen is to filter whole blood, removing old, malformed, or damaged red blood cells as well as bacteria from circulating blood. Just like any other organ, the spleen is susceptible to disease. Mononucleosis, or mono, can have devastating effects on the spleen.

Mononucleosis is a disease caused by the Epstein–Barr virus. It is spread through contact with saliva, which is how it earned the nickname of the kissing disease. On any given campus 1–3% of the population will contract mono each year, making it a well-known disease among young adults. Symptoms of the disease include headache, fever, sore throat, swollen lymph nodes in the back of the neck and under the arms, and extreme fatigue. Once infected, the virus must run its course, a process that can take anywhere from a few weeks to a few months. A hidden symptom of this disease that occurs in approximately half the cases is an enlargement of the spleen. Normally the soft, pulpy spleen is tucked up under the ribs. When it enlarges, however, this delicate organ hangs below the ribcage and is exposed to damaging blows. In this enlarged state, the spleen is even more soft and delicate. Sudden jarring of the body, such as what happens when participating in contact sports, heavy lifting, or jumping on a trampoline, could rupture the spleen. If the spleen tears slightly, a slow blood loss will occur that results in lower blood pressure, lightheadedness, and confusion. More strenuous movements can cause complete rupture. This leads to life-threatening internal bleeding that can only be stopped medically.

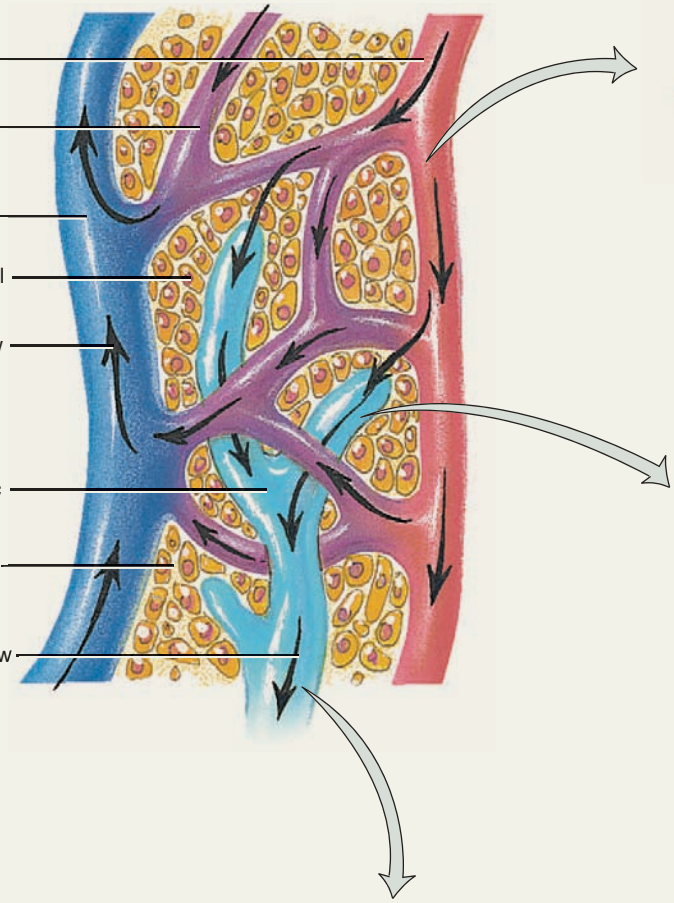
Your tissues are bathed in **lymph**, a clear fluid that is called interstitial fluid when it is found in the **interstices** between cells. Chemically, lymph is quite similar to blood plasma, which makes sense because lymph originates in fluid that diffuses from the capillaries into the tissue. If you scrape your epidermis—say, when you "skin your knee"—clear interstitial fluid will bead up on the exposed dermis. Normally, lymphatic vessels collect this fluid for return to the bloodstream. When interstitial fluid is inside lymph vessels, we call it lymph.

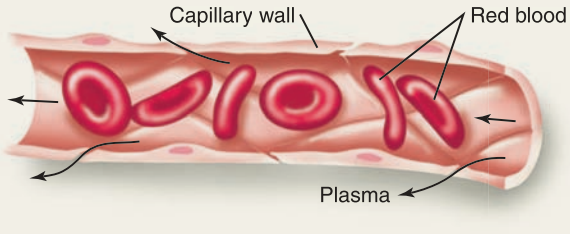
interstices The small fluid-filled spaces between tissue cells.

Lymphatic Capillaries and Vessels Resemble a Parallel Circulatory System

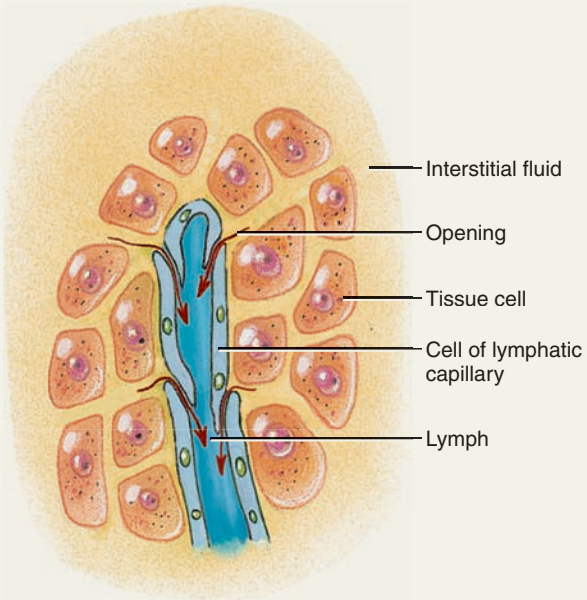
The lymphatic system has many similarities to the circulatory system, because both systems reach almost every cell in the body. Because interstitial fluid is so widespread,

Relationship of lymphatic capillaries to tissue cells and blood capillaries

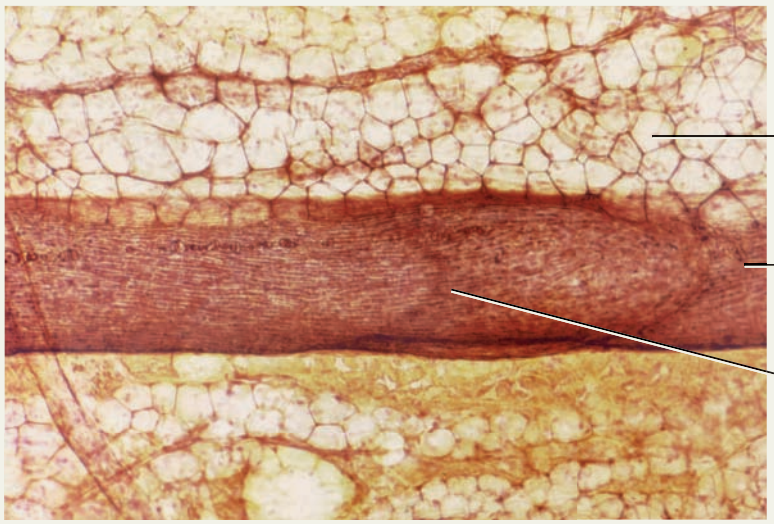




1 Blood pressure forces the fluid portion of the blood out at the capillaries, bathing the tissues.



2 The excess fluid is then forced into the lymphatic capillaries from the tissues by fluid pressure and osmotic pressure.



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3 The fluid already in the lymphatic vessel opposes the mass movement of tissue into the lymphatic system, helping to keep the tissues moist. Lymph flows without being pumped, and valves prevent backflow.

lymphatic **capillaries** (very small vessels) are also found throughout the body. Often, the lymph in these capillaries is filled with ingested fats, turning the vessel milk white.

In the circulatory system, capillaries are part of a closed system that takes blood from the heart to the body and back to the heart. Larger vessels attach to either side of a capillary. In contrast, lymphatic capillaries are small tubes with one closed end and one end leading to a larger lymphatic vessel. They are part of an **open system** in which vessels lead from the tissues to the bloodstream but not in the opposite direction.

open system
A system with a starting point and an ending point rather than a continuous circular flow.

Unlike the circulatory system, the lymphatic system has no central pump. Lymph flows through tissues and into lymphatic capillaries mainly because of the squeezing action of skeletal muscles. As muscles contract, they shorten and thicken, forcing excess fluid from the muscular tissue and surrounding organs into the lymphatic capillaries. Lymphatic capillaries allow fluid to enter but not to exit, because their walls are composed of cells positioned with slight overlaps. See Figure 9.14. Pressure from outside the vessel parts the cells so that fluid can enter the lumen (center) of the capillary. Fluid pressure inside the capillary presses the cells shut so that the fluid cannot escape. This action is rather like your front door. If you push on one side, the door will open, but if you push from the other side, it will only close tighter.

Lymphatic vessels are similar to the veins, which are thin-walled, flexible, and not built to withstand much pressure. Because lymph flows through the lymphatic system without being pumped, larger lymphatic vessels require **valves** to prevent backflow.

Lymphatic vessels transport their lymph to either the thoracic duct or the right lymphatic duct, just posterior to the right clavicle. Both ducts drain into the subclavian veins, allowing lymph to return to the bloodstream. The right lymphatic duct drains the right side of the head, the right shoulder, and the upper portion of the right chest, as shown in Figure 9.15. Lymph collected from the rest of the body is drained into the thoracic duct. This arrangement causes concern for breast cancer patients, whose cancer may metastasize into the lymph. If this happens, it is easy to see how quickly those cells can be spread throughout the body via the lymphatic system.

Lymphatic Organs Filter and Protect

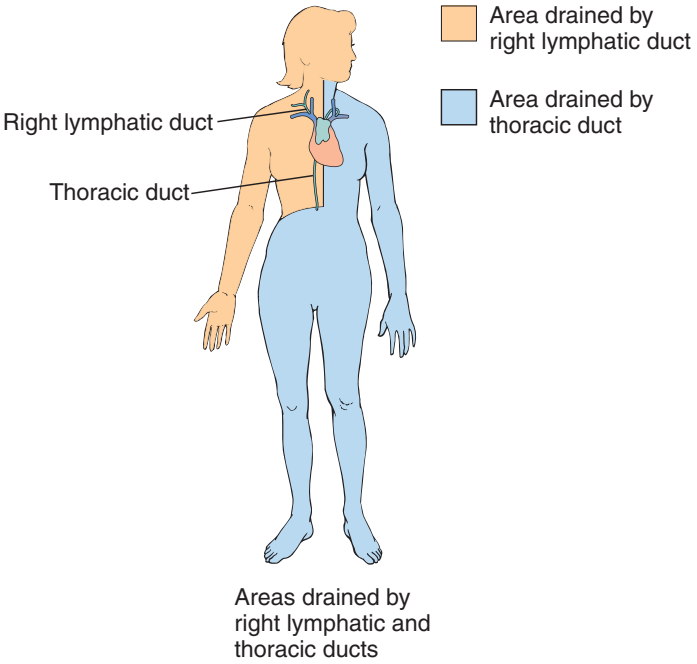
Before lymph returns to the bloodstream, it must be filtered and cleaned. Otherwise, the lymph would dump into the bloodstream the cellular debris and waste products it has picked up while traveling through the tissues. This cleaning occurs in the lymphatic organs—the lymph nodes, tonsils, spleen, thymus gland, and bone marrow.

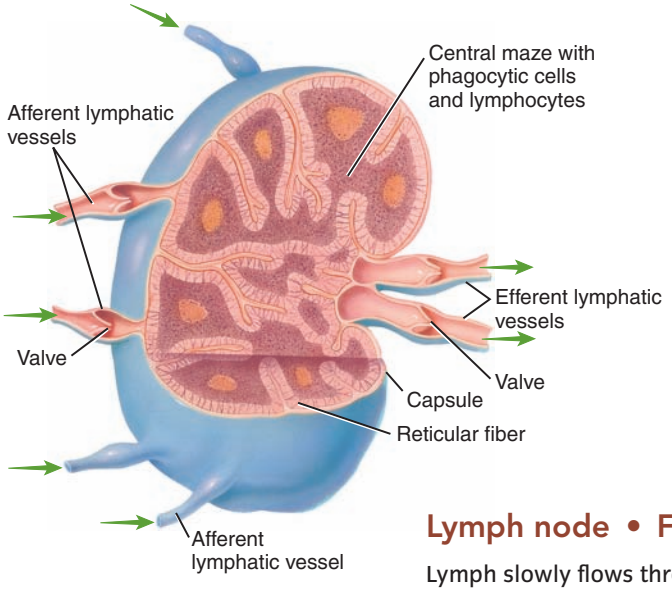
Lymph nodes are cleansing units.

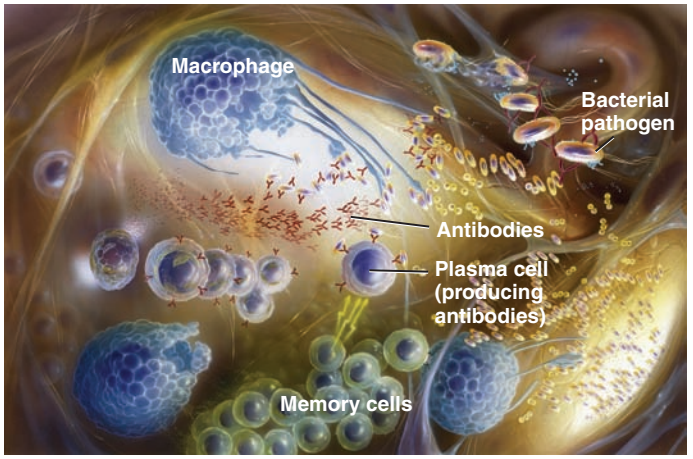
Lymph nodes are small, encapsulated glands that are strategically located to filter large volumes of lymph. Some are found in the groin, some in the armpit, and some are in the neck. The **mesenteric** lymph nodes form a chain at the center of the abdominal cavity.

mesenteric
Pertaining to the membranous fold in the abdominal cavity attaching many of the abdominal organs to the body.

Areas drained by the lymphatic ducts • Figure 9.15







Lymph node • Figure 9.16

Lymph slowly flows through a maze inside the node, giving phagocytic cells in the lymph node time to interact with the fluid and remove and destroy infectious agents and debris.

Nodes are filtering stations for lymph, as shown in Figure 9.16. Lymph enters a node via many passages but can leave by only one or two exits, forcing lymph to flow through the nodes in one direction.

Lymph nodes filter lymph that has been collected from nearby tissues, therefore they can tell us a good deal about the health of that region of the body. "Swollen glands" are lymph nodes that are enlarged due to localized or systemic infection, abscess formation, malignancy, or other, rarer causes. A bacterial infection can often be detected in the lymph, because immune cells in lymph nodes increase in number and produce antibodies.

Many infections can cause swollen lymph nodes, including mononucleosis, German measles, tuberculosis, mumps, ear infections, tonsillitis, an abscessed tooth, gingivitis (infection of the gums), large and untreated dental cavities, and various sexually transmitted diseases. Immune disorders that can cause swollen lymph nodes include rheumatoid arthritis and HIV. Cancers that can cause swollen glands include leukemia, Hodgkin's disease, and non-Hodgkin's lymphoma. Swollen lymph nodes may also be caused by certain medications or vaccinations. Cells of certain cancers, especially breast cancer, can be found in lymph nodes near the site of the primary tumor. As these cells metastasize, or migrate, to form new tumors, the number of lymph nodes containing cancer cells increases. This then is a good indicator of how advanced the cancer is.

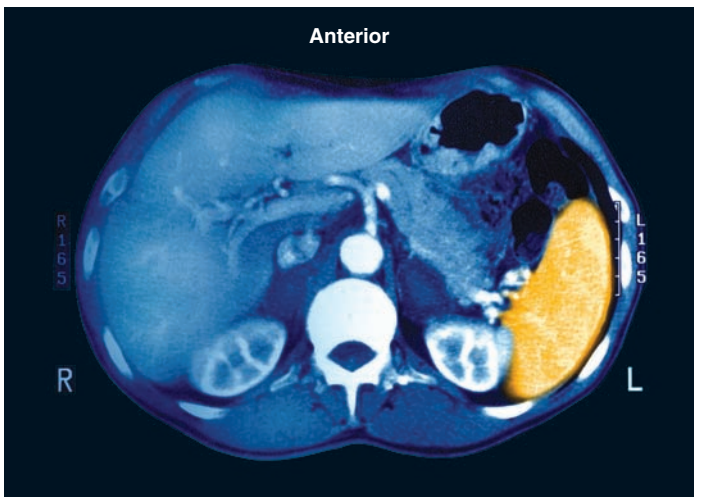
Tonsils and MALT are patches of unencapsulated lymphatic tissue. The **tonsils** are similar to lymph nodes in their organization and function. You were born with three sets of tonsils: the pharyngeal tonsils in the nasopharynx, the palatine tonsils, which are visible on either side of the pharyngeal opening, and the lingual tonsils found on the base of the tongue. The main difference between tonsils and lymph nodes is that the tonsils are not entirely encapsulated. Instead, they are open to the fluids that pass through the throat. Infectious agents can be trapped in these organs, swelling the tonsils enough to almost shut off the throat.

Similar patches of lymphoid tissue are found in the lining of the small intestine. These egg-shaped masses, called mucosa-associated lymphoid tissue, or **MALT**, help filter fluid absorbed from the intestinal lumen.

The largest lymphatic organ is the spleen. The largest collection of lymphoid tissue in the body is the fist-sized spleen—see Figure 9.17. The spleen has a strong

Spleen • Figure 9.17

The spleen is highlighted in yellow in this CT scan.



outer capsule surrounding red and white pulp. Red pulp, containing red blood cells and macrophages, purifies blood by removing bacteria and damaged or exhausted red blood cells. The white pulp contains **lymphocytes** and is involved in specific immunity. For this reason, the spleen is considered a lymphatic organ, even though it filters whole blood rather than lymph.

lymphocytes
White blood cells that patrol the body, fight infection, and prevent disease.

The thymus produces mature immune cells. The thymus gland is located in the thoracic cavity, behind the sternum and draping over the upper portion of the heart. It is composed of two lobes held together by connective tissue, as seen in **Figure 9.18**.

The primary function of the thymus is to produce mature, functional T cells, a distinct group of immune cells. The cortex of the thymus gland is involved in "training" T cells to distinguish self from pathogens. It also produces thymic hormones that promote maturation of T cells.

Bone marrow also produces mature immune cells. The final type of lymphatic tissue is red bone marrow. In children, red bone marrow is found in the center of virtually all the bones. When we reach adulthood, only the skull bones, sternum, ribs, clavicle, epiphyses of the femur, pelvic bones, and the vertebral column retain red marrow. The remaining bones contain yellow marrow in their marrow cavities. Red bone marrow includes blood **stem cells** that can produce both red and white blood cells. The cells involved in specific immunity are a subset of these white blood cells.

stem cells
Undifferentiated cells that remain able to divide and specialize into functional cells.

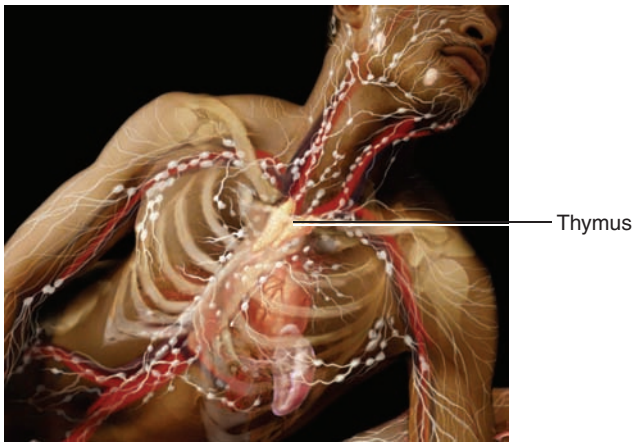
As we now understand, the lymphatic system cleans and returns excess fluid to the circulatory system. It is also of paramount importance in maintaining homeostasis through its role in specific immunity.

Specific Immunity Relies on a Series of Deadly Cells that Recognize and Remember Pathogens

When a pathogen slips past our nonspecific defenses, the battle is not over. Rather than immediately succumb to the disease, we rely on our specific defense—the immune system. This system is composed of a set of blood cells collectively called lymphocytes. The various subtypes of

Thymus • Figure 9.18

The thymus is largest at puberty and shrinks with age, losing function as it shrinks. One reason your parents or grandparents probably suffer more than you from a common cold or a passing virus is thymic atrophy.



lymphocytes look alike but have subtly different functions. Immune cells share common characteristics, including:

- The ability to distinguish self from nonself (otherwise, immune cells would destroy the very fabric on which they depend).
- Specificity, meaning each one reacts only to a particular antigen (a component of a disease-causing agent).
- The ability to remember certain pathogens and react more quickly the second or subsequent times the pathogen is encountered. This is the basis for **immunization**.

immunization
The process of stimulating resistance to a specific disease through exposure to a nonpathogenic form of the disease-causing organism.

The specific immune system (now referred to simply as the "immune system") has two methods for combating pathogens, both of which are carried out by lymphocytes. In one method, referred to as **cell-mediated** (or cellular) immunity, specialized lymphocytes function directly in any pathogen attack. In the other method, called **antibody-mediated** (or humoral) immunity, specialized lymphocytes function indirectly by helping create disease-fighting compounds called **antibodies**.

antibodies
Proteins produced by lymphocytes and directed against specific pathogens or foreign tissue.

There is some evidence that we can boost both kinds of immunity. See *I Wonder… How Can I Boost My Immune System?* on the following page.

WILEY PLUS Video

I WONDER...

How Can I Boost My Immune System?

We see it all the time: health foods claiming to boost our immune systems or help us fight off colds and flu. Is there a grain of truth in these claims?

Current research has shown that our immune systems may in fact be functioning below par and will respond favorably to homeopathic (natural) remedies. We already know that broccoli is good for us—it contains vitamins and minerals, such as calcium and vitamin K, that may be otherwise lacking in our diets. Now scientists have found that another compound, DIM or diindolylmethane, specifically enhances the functioning of our immune system. Putting this compound into health drinks might actually increase immune functioning as advertised!

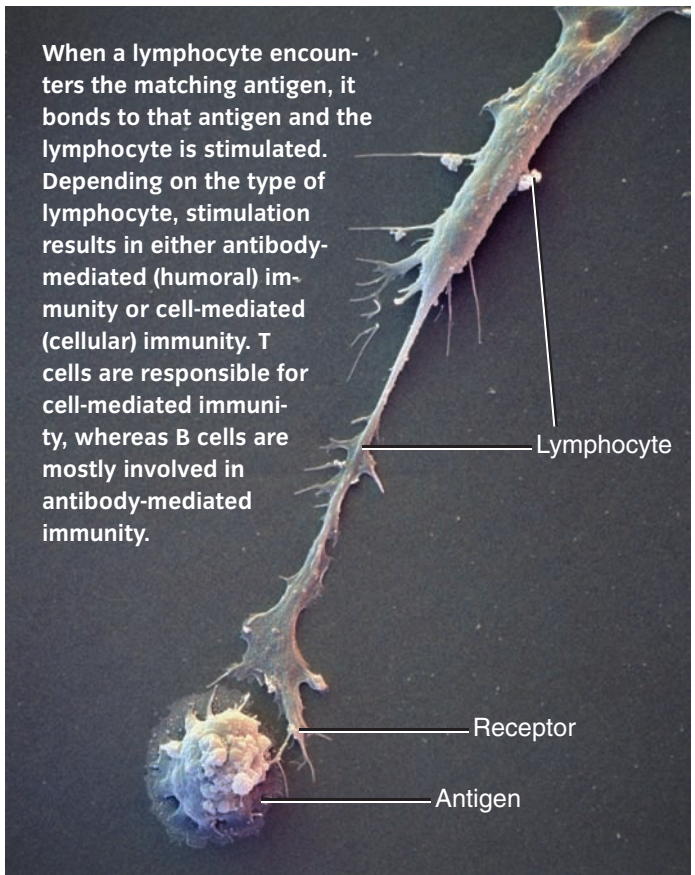
In 2003, researchers discovered that compounds found in green tea speed up the immune response, allowing us to fight bacterial infections more efficiently. Another interesting study, using mice as subjects, reported an increase in the ability to get over the flu after experiencing social stress. The researchers noted that mice exposed to a particularly aggressive cagemate were able to get over flu symptoms far more quickly than their nonstressed counterparts. This finding is more difficult to explain, as it seems to indicate that triggering the GAS increases immune sensitivity. Such an approach might also be difficult to market: "Come let us annoy you for a few hours every day, and you will be healthier!"

The immune system uses two kinds of assassins.

Two main classes of lymphocytes are involved in immunity: B cells and T cells. B cells (B lymphocytes) mature in the bone marrow (hence the "B" designation) and spend most of their time inside lymph nodes and interstitial fluid. B cells produce antibodies that are specific to a particular pathogen, and so are usually considered part of antibody-mediated immunity. T cells (T lymphocytes) mature in the thymus gland (hence the "T" name) in response to thymic hormones. T cells make up about half of the circulating lymphocytes in the blood, and they do not produce antibodies. T cells are responsible for stimulating B cells, as well as the direct destruction of antigens. T cells are most associated with cell-mediated immunity.

Lymphocytes have receptors on their cell membranes waiting to detect the exact antigen that fits the receptor like a lock and key, as shown in **Figure 9.19**. Each lymphocyte is specific to one antigen; it will ignore all others. During our lives, we are constantly exposed to antigens. Amazingly, our lymphocytes develop a specific response to every one of them by mixing and matching the genes

Lymphocyte with antigen attached to receptor • Figure 9.19



When a lymphocyte encounters the matching antigen, it bonds to that antigen and the lymphocyte is stimulated. Depending on the type of lymphocyte, stimulation results in either antibody-mediated (humoral) immunity or cell-mediated (cellular) immunity. T cells are responsible for cell-mediated immunity, whereas B cells are mostly involved in antibody-mediated immunity.

that create the receptor proteins of the immune system. Small changes in receptor shape on the surface of a T cell or B cell will cause that cell to react to a different antigen.

Antibody-mediated immunity involves B cells. Antibody-mediated immunity has an alternative name, humoral immunity, which reflects the fact that this immunity takes place in the fluids or "humors" of the body. Antibodies are proteins that remove antigens from the bloodstream, usually by causing them to **agglutinate**. Each B cell produces a different antibody that is directed toward a specific antigen. Because the B cell "wears" this antibody on its surface, the antibody is called a marker. When the surface antibody reacts with its specific antigen, the B cell is activated and begins to divide, cloning itself. Because the antigen in effect "chooses" or selects which B cell will be cloned, this process is called clonal selection.

agglutinate To clump with other cells due to the adhesion of surface proteins.

The cloned B cells produced during clonal selection are identical to the original, so they will react to the same antigen that started the cloning in the first place. As the cloned B cells are produced, two populations are created: plasma cells and memory cells. Mature antibody-producing B cells, called plasma cells, pump out an arsenal of antibodies directed against the specific antigen that stimulated the original B cell, ensuring that the antigen is removed from the body, as shown in **Figure 9.20**. When the antigen is gone, the plasma cells undergo **apoptosis** and die.

apoptosis Programmed cell death.

The second variety of cloned B cells, called memory cells, contributes to a library of long-term immunity that we call the secondary immune response. For as long as 10 years, memory cells stand ready to go into action. If the pathogen reappears within that period, the memory cells quickly produce antibodies, ready to combat the pathogen before it can cause harm. Vaccinations and booster shots are **attenuated** pathogens, designed to carry the "look and feel" of a harmful pathogen, but without the ability to cause disease. Your body will respond as if the attenuated pathogen were still capable of causing illness, cloning the proper B cell and producing both plasma and memory cells. Importantly, these shots trigger the formation of memory cells, thus allowing us to fight pathogens that have never actually caused us to get sick. We have memory cells for a disease whose symptoms we have never actually experienced.

attenuated Reduced capability of a pathogen to cause disease.

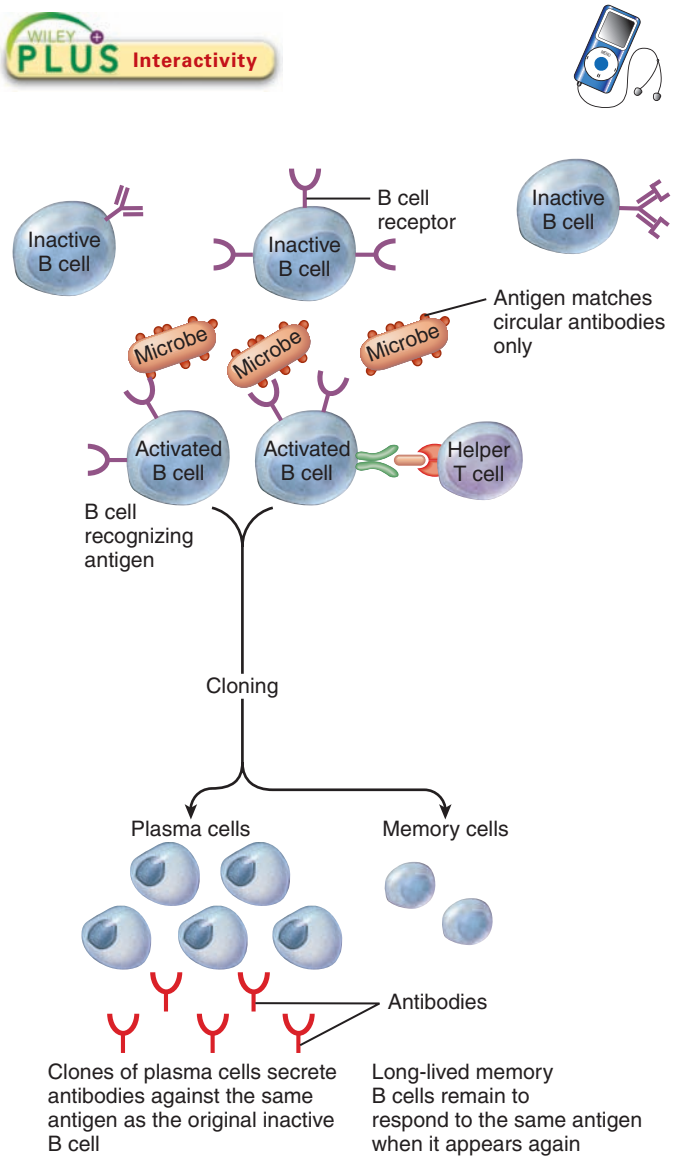
Antibodies are more specific than your social security number. Antibodies are proteins secreted by plasma cells in response to antigen binding. Antibodies all

PROCESS DIAGRAM

THE PLANNER

B cell activation • Figure 9.20

WILEY PLUS Interactivity



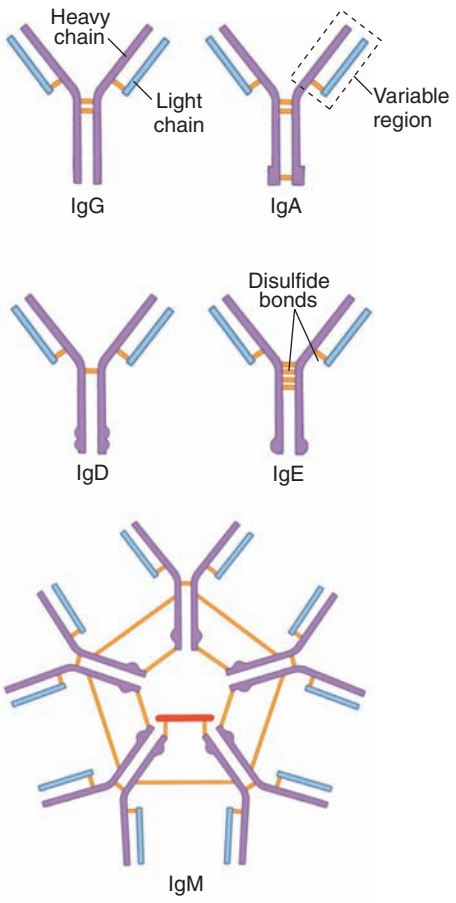
have the same general shape: a doubled, Y-shaped protein with one heavy chain and one light chain polypeptide.

The upper tips of the heavy chain and the corresponding tips on the light chain identify each antigen, and because they change so much, they are called the variable region. It is the variable region that interacts with the antigen and causes agglutination. A large conglomeration of antigen and antibody marks the antigens for destruction by the macrophages.

The five classes of antibodies (also called immunoglobulins) are IgG, IgM, IgA, IgD, and IgE, as shown in Figure 9.21.

- IgG, by far the most common antibody, occurs in the circulating blood, lymph, and extracellular fluid. IgG immunoglobulins bind directly to an antigen, inactivating it almost immediately.
- IgM is the first immunoglobulin released in any immune response and is also the predominant immunoglobulin produced in infants. IgM is a large polymer of five Y-shaped molecules that causes infected or foreign cells to clump together when IgM binds to them. Like IgG, IgM also aids in the release of complement.
- IgA can be a monomer, dimer (two subunits), or larger molecule composed again of Y-shaped units. One form of IgA, found in secretions, such as saliva, can bind to pathogens before they enter the bloodstream.
- IgD, found on mature B cells, binds antigens that stimulate B cell activation.
- IgE, the immunoglobulin responsible for immediate allergic reactions, appears on the surface of basophils and mast cells, both of which release histamines and other chemicals implicated in allergic symptoms.

Five classes of antibodies • Figure 9.21



In the body, natural antibody-mediated immunity results when many different plasma cells are simultaneously stimulated to form antibodies. Each clone of plasma cells originates from a different B cell. Each of these plasma cells produces an antibody that responds to a slightly different portion of the invading pathogen. The resulting soup of antibodies is polyclonal, meaning that the antibodies are produced by many different plasma cells. Polyclonal antibodies are directed against one specific antigen, but they link to many different antigenic sites on that antigen. Directing so many slightly different antibodies against differing portions of the same antigen ensures that no antigen will be left in the bloodstream.

Because antibodies are specific, they are an interesting source of precisely targeted drugs. Most of these cutting-edge medical treatments propose to use "monoclonal antibodies." As the words imply, monoclonal antibodies are antibodies that are formed from clones of a single activated cell. The idea is to deliver the death knell directly to the diseased cells without harming healthy cells.

The specificity of monoclonal antibodies is often used in medical tests. The pregnancy tests sold in drugstores use a monoclonal antibody directed against a protein found only in the urine of pregnant women. Because monoclonal antibodies are so specific, any reaction in the test proves that the woman is pregnant. (If there is no reaction, the test should be repeated within a few days, because the protein level could be too low to detect on the first test.)

Cell-mediated immunity involves two kinds of T cells. Cell-mediated immunity is governed by the T cells that are carried through the tissues of the

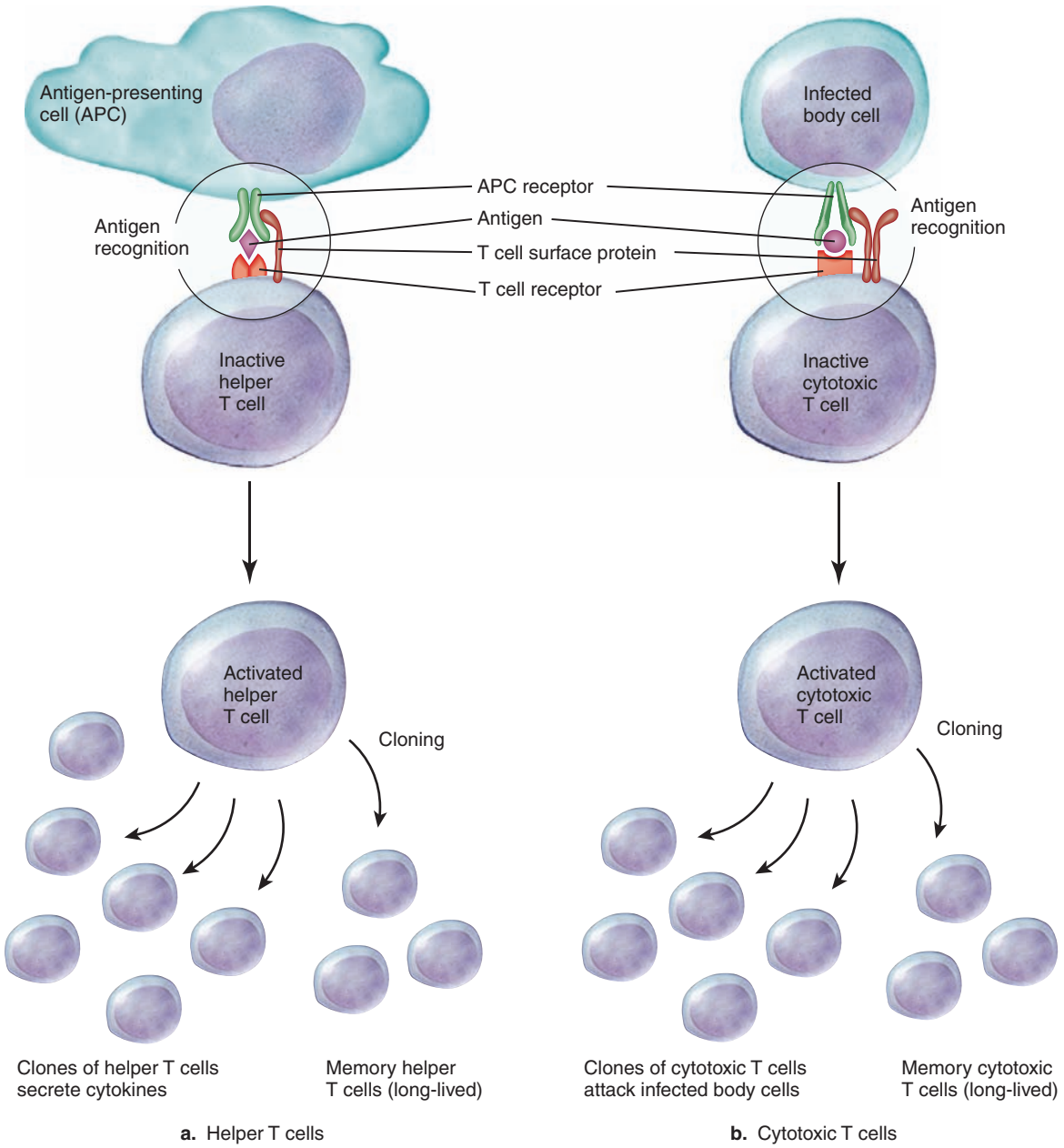
blood. There are two large populations of T cells: helper T cells and **cytotoxic T cells**. See Figure 9.22.

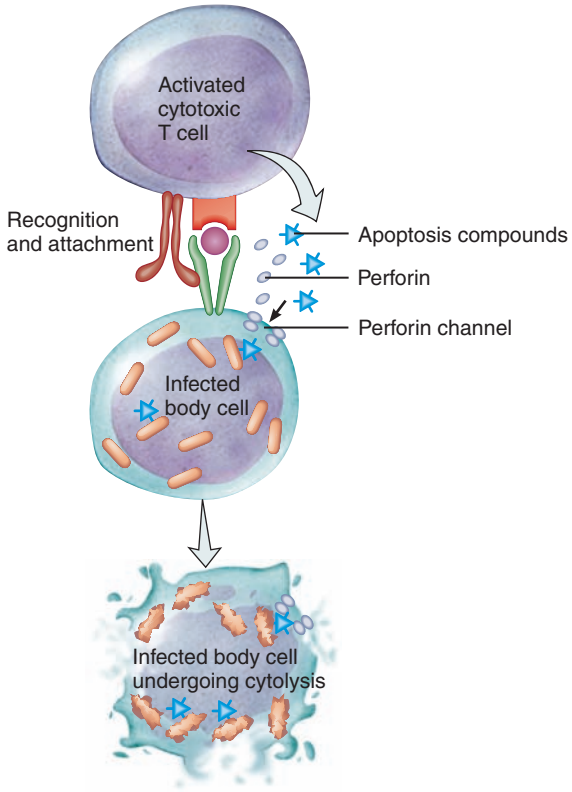
cytotoxic T cells Subset of T lymphocytes responsible for killing virally infected cells.

Unlike B cells, which can directly detect the presence of an antigen using the antibodies on their surface, T cells must have the antigen presented to them. This is done by antigen-presenting cells (APCs), which are usually macrophages. The APC encounters an antigen, phagocytoses it, and "presents" or wears a portion of that antigen on its surface. APCs present their ingested pathogens using a specific membrane protein complex. Just like B cells, T cells carry receptors on their surface that will bind to specific antigens. However, these T cell receptors only recognize antigens presented on the surface of an APC. T cells that recognize the APC-presented pathogen are stimulated to differentiate into either helper T cells or cytotoxic T cells. The cytotoxic T cell will seek out and destroy the stimulating pathogen wherever it occurs in the body.

T cell activation • Figure 9.22

a. Activation of helper T cells required an antigen-presenting cell (APC). The APC binds an antigen and then is able to activate a helper T cell through the T cell receptor and the cell surface protein.
b. Activation of cytotoxic T cells is similar but begins with an infected body cell presenting the antigen.





Cytotoxic T cell destruction of infected cell by release of perforins that cause cytolysis; microbes are destroyed by other released chemicals.

Perforin • Figure 9.23

Stimulated helper T cells will travel through the blood and lymph to the lymph nodes, where they will in turn stimulate the matching B cell. In this way, they are helping to bring the antigen to the specific B cell equipped to produce antibodies to destroy it. When activated, both kinds of T cells make copies of themselves to fight pathogens and also produce memory cells for fighting future invasions. These memory cells lie in wait in the blood, ready to jump quickly into action should the same antigen again threaten the body.

cytokines Chemical signals released by immune cells during the immune response.

Cytotoxic T cells are stimulated to divide by **cytokines** released from helper T cells. Cytotoxic T cells respond specifically to altered HLA (human leukocyte antigen) proteins. The HLA complex is a marker that identifies the cell as belonging to the body and is what we identify when we "tissue type" a person to find a matching organ before an organ transplant. During organ transplants, HLA mismatches can trigger a rejection reaction by cytotoxic T cells. Incorrectly matched tissue types can lead to complete destruction of foreign HLA-carrying transplanted organs.

Most cells in the body with foreign HLA complexes are not introduced during organ transplants but rather are cancerous or virally infected. Cytotoxic T cells will remove any cell without the proper HLA antigens, whether cancerous, infected, or beneficial to the body. Cytotoxic T cells, or killer cells, physically attach to the foreign HLA-carrying cell and release **perforin** molecules from their vacuoles. Perforin molecules are like little molecular darts that poke through the plasma membrane of the infected cell, as shown in **Figure 9.23**. A pore forms in the cell membrane, allowing salts and water to enter the cell, causing it to swell and burst.

Some T lymphocytes differentiate into natural killer cells. Natural killer (NK) cells are actually part of our innate defense system. They are introduced here because they are produced exactly like the helper T cells of our specific immune defenses. NK cells function as a natural cancer screen, patrolling the body and identifying virally infected cells and tumor cells. After detection, NK cells kill the diseased cell via cell-to-cell contact. This contact is carried out by proteins. As with the cytotoxic T cell, perforin is released by the NK cell, creating pores in the doomed cell. Along with perforin, other proteins are released that induce apoptosis when taken into the target cell. These apoptosis-inducing proteins are absorbed by the target cells once perforin has punctured their membranes. NK cells are not part of the specific immune response because they remove all foreign or infected cells in exactly the same way. They do not respond to immunization, and they do not seem to produce clones of memory cells.

There is some evidence that our emotions and thoughts can affect our immune systems, possibly by suppressing the T cells when we are stressed and enhancing our T cells when we are particularly upbeat. See *Ethics and Issues: How Do Thoughts and Emotions Affect Our T Cells and Immune Systems?*

CONCEPT CHECK STOP

1. **How** do the structures of the lymph, lymphatic vessels, and lymphatic organs relate to their functions?
2. **How** do lymphatic and blood vessels differ?
3. **What** are the steps involved in cellular and humoral immunity?
4. **What** are the functions of plasma cells, memory cells, helper T cells, and cytotoxic T cells?

ETHICS AND ISSUES

How Do Thoughts and Emotions Affect Our T Cells and Immune Systems?

Are you happy? Sad? Sleep deprived? Stressed out? Worried sick?

There is evidence that your mind can have a large impact on your health. From your general demeanor to how you handle the slings and arrows of life—job loss, death of a loved one, breakup of a relationship—your emotional and mental health has a subtle yet pronounced effect on your immune system.

The earliest evidence was anecdotal. Doctors noticed that people who suffered from depression as well as another physiological illness, such as heart disease, diabetes, or AIDS, needed more intense medical treatment and often experienced higher rates of disability and death than people with the same illnesses but no depression. Also, people who were convinced that they were going to get sick actually got sick at a higher rate than those who believed that they would be healthy. These observations led to clinical studies and basic scientific research on how the mind affects the body.

One study involved 34 college students who were told that an electric current would be passed through their heads and that they might feel headaches as a result. No current was actually used, but more than two-thirds of the students reported headaches. The nocebo effect (*nocebo* is Latin for "I will harm") is the opposite of the better-known placebo effect, in which a drug or treatment makes a patient feel better merely because the patient *believes* that it is going to work. The nocebo effect occurs when patients think that their health will worsen because of a drug or treatment, and as a result their health deteriorates despite the absence of an immediate physical cause.

What could link the mind to the body and the immune system? We have seen that the release of hormones is a natural reaction to stress. Some studies have shown that releasing excess stress hormones makes the immune system work less efficiently by lowering the number and activity level of some kinds of T cells, and there is some evidence that thinking positively actually may raise the killer T cell count over time.

Critical Reasoning Issues Unlike placebo-based experiments, experiments testing the nocebo effect are usually unethical, since a doctor or experimenter should not deliberately cause harm or illness. Hence, there are no large studies of the nocebo effect with large samples of patients. Small studies and anecdotes have provided all the available evidence so far.

Think Critically

1. Can you design an ethical study of the nocebo effect?
2. Some colleges and universities have reduced library hours during final-exam period. "Wellness" officials urge students to sleep more and spend time "de-stressing." Can such efforts actually backfire, causing more stress? Should students be allowed to manage the sleep/study balance for themselves?
3. "Aging in place," allowing the elderly to remain in their own homes with home healthcare, is a way of reducing healthcare costs. However, evidence shows that social contact reduces stress and thus has an impact on health. Should we be encouraging older people to live in elder communities, where they can increase their social contacts?

NATIONAL GEOGRAPHIC

9.5 Immunity Can Be Acquired Actively or Passively

LEARNING OBJECTIVES

1. **Define** the primary and secondary immune responses.
2. **Compare** active and passive immunity.
3. **Describe** the action of autoimmune diseases.

Most of us acquire immunity from experience. We are exposed to a pathogen, it invades our tissues, and our immune system counterattacks by making antibodies (as just described). This is natural **active immunity:** Your immune system is exposed to the antigen in the natural course of your life; your immune cells respond and actively combat the pathogen. **Passive immunity**, in contrast, occurs when antibodies are transferred without stimulating the immune system.

Active Immunity Is the "Trainable" Immune System

The primary advantage of active immunity comes from the creation of memory cells, which arise many hours after the initial reaction to the pathogen. Initially, the body needs days to respond to the pathogen, stimulate the proper cells, and follow the chain through helper T cells to B cells to plasma cells to antibody production. Then the body needs a few more days of antibody production to elevate the antibody **titer** to an effective level.

titer Level of a compound or antibody in the blood.

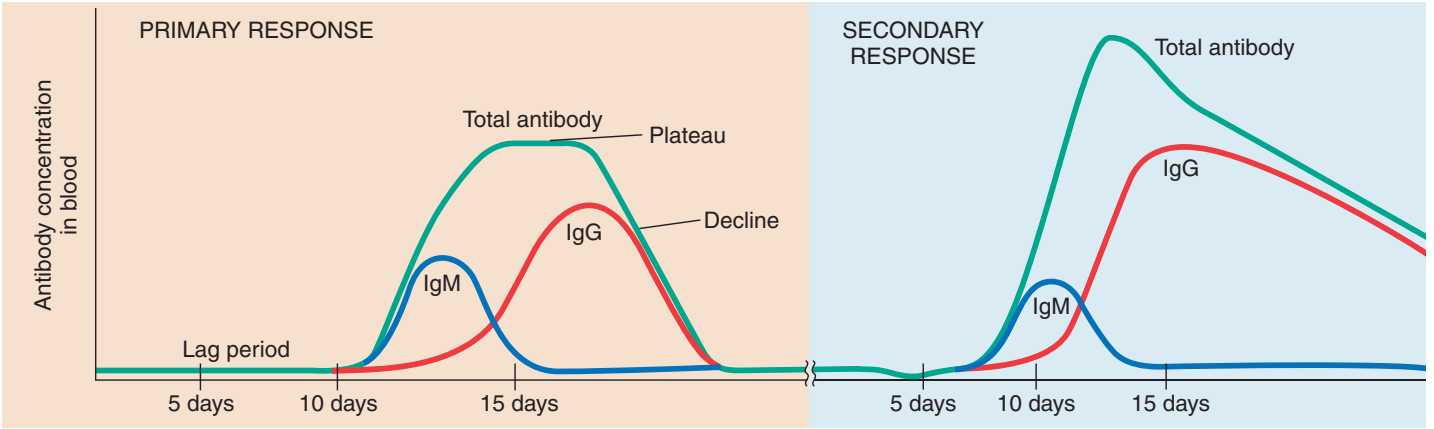
Memory cells produced during the primary response remain in the body for years, lying dormant until the same antigen reappears, when they will start the secondary response. This secondary response to a particular antigen happens far faster than the first response, because the immune system needs to stimulate and clone only the memory cells—see **Figure 9.24**. Secondary responses also require less energy from the body.

Although active immunity can prevent illness from a second exposure to a pathogen, the process we have described requires that you have previously been exposed to the pathogen, gotten sick, and recovered. It's preferable to prevent illness from the outset, so we never get the disease; some pathogens, after all, are extremely fatal! Fortunately, immunity can be obtained through artificial means as well. In that case, we intentionally introduce a pathogen to the body rather than allow you to contract the pathogen naturally. These pathogens are attenuated so that they can stimulate a primary immune response without causing disease.

Passive Immunity Gets Help from the Outside

As noted in the previous section, passive immunity is the transfer of antibodies without stimulating the immune system. Although active immunity is helpful because the memory cells can launch a quick secondary response,

Response time for primary and secondary responses • Figure 9.24



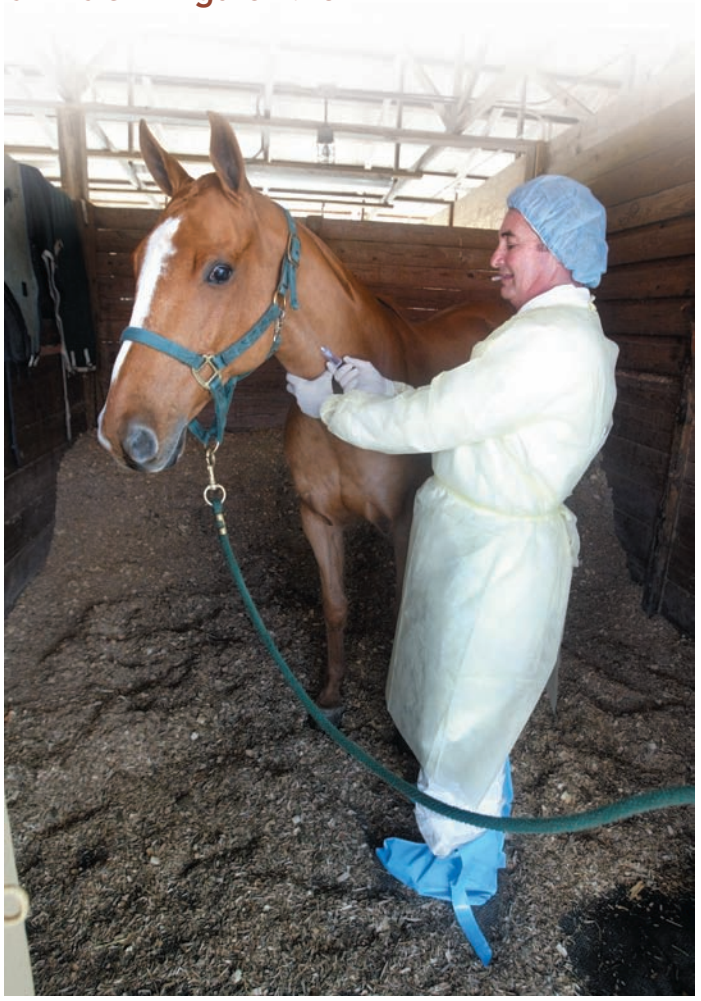
passive immunity is also beneficial because you do not expend energy creating antibodies or producing clones. However, passive immunity is like giving an infantryman a gun with only one magazine. Introduced antibodies provide the recipient with immediate resistance to specific antigens. Once the antibodies are used or broken down, however, the body cannot create more, and the immune protection is lost. There are no memory cells, because the antibodies were not created by active stimulation of the immune system.

La Leche League is a nonprofit organization that promotes healthy prenatal and postnatal care for both the infant and the mother. Their best-known campaign is designed to educate women on the advantages of breastfeeding until at least age 6 months. The antibodies received by the baby from the maternal blood in utero sustain the infant for approximately two to three months. Soon after, these antibodies begin to break down, and the infant must either produce antibodies via active immunity or receive maternal antibodies via breast milk. See **Figure 9.25**. Breastfed infants continue to gain passive immunity from their mothers and are therefore more able to resist disease. Infant formula may have a nutrient content similar to human milk, but it does not contain any antibodies.

Nursing baby • Figure 9.25

Passive immunity can be acquired naturally, when maternal antibodies pass through breast milk to an infant, which is one reason La Leche League and many doctors encourage breastfeeding.

Passive immunity: Harvesting antibodies produced by the immune systems of other animals • Figure 9.26



Passive immunity can be used to fight diseases that cannot be fought in any other way. Horses, goats, rats, mice, and rabbits have all been used to generate antibodies against specific human diseases—see **Figure 9.26**. These animals are given vaccines causing them to produce antibodies, just as we do. The antibodies in the animals' blood are harvested, purified, and administered to humans for treating diseases, such as diphtheria, botulism, and tetanus.

Passive immunity can also be administered artificially in gamma globulin shots, which are mixtures of many antibodies designed to match the pathogens the patient may contact. These are often given before travel to foreign countries, where new diseases may be encountered. Passive immunity generally lasts three to six months, long enough for most foreign vacations.

In Autoimmune Diseases, Defense Becomes Offense

The immune system is a complicated network of cells and cell components that normally defend the body and eliminate bacterial, viral, and other pathogenic infections. This sophisticated mechanism goes awry in autoimmune disease, when the immune system mistakenly attacks the body's own cells, tissues, and organs. *Auto* is Greek for "self," so an autoimmune response is an immune response in which the body attacks itself.

The many autoimmune diseases have different effects depending on what tissue is under attack. In multiple sclerosis, the autoimmune attack is directed against nervous tissue. Immune cells break down the myelin surrounding neurons of the CNS, resulting in the buildup of scar tissue that impedes normal impulse transmission. Crohn's disease is an autoimmune disease directed against the absorptive portion of the gut. Type I diabetes mellitus is an autoimmune disease that attacks the pancreas. If the pancreas is not functioning properly, cells of the body cannot absorb glucose as they should, resulting in the myriad symptoms of diabetes.

In diseases like systemic lupus erythematosus (lupus), the site of the attack may vary. In one person, lupus may affect the skin and joints, and in another it may affect the skin, kidney, and lungs. Rheumatoid arthritis is an extremely common autoimmune disease, attacking the joint capsules of the body, causing painfully deformed joints. Although this type of arthritis is usually considered a disease of older people, 1 in 1,000 children under the age of 16 show signs of juvenile rheumatoid arthritis.

The damage of autoimmune disease may be permanent. Once the insulin-producing cells of the pancreas are destroyed in Type I diabetes, they do not regenerate. Autoimmune diseases afflict millions of Americans, and for reasons not understood, they strike more women than men. Some autoimmune diseases are also more frequent in certain minority populations. For example, lupus is more common in African American and Hispanic women than in Caucasian women of European ancestry. Rheumatoid arthritis and scleroderma, another autoimmune disease, affect a higher percentage of some Native American communities than the general U.S. population.

CONCEPT CHECK 

1. **Why** is the secondary immune response so much more effective than the primary immune response?
2. **How** do active and passive immunity differ?
3. **What** is the action of autoimmune diseases?

Summary

1 How Do We Adapt to Stress? 212

- Humans face many types of stress from physical, emotional, social, or microbial sources.
- We have many systems to deal with stress, including the skin, whole-body and localized reactions, and a variety of chemical and physical mechanisms to reduce, eliminate, or survive stress.
- As shown in this diagram, the body responds to stress with the three stages of the General Adaptation Syndrome: alarm, resistance, and exhaustion. During alarm, the fight-or-flight mechanism predominates. This stage tries to remove the body from the stressor. If unsuccessful, the resistance phase begins. During this phase, blood ion concentrations are pushed far from homeostasis in an attempt to maintain elevated blood glucose. Should resistance continue for a prolonged period, the body will reach exhaustion. During exhaustion, the body retreats from the fight and tries to recover from the al-

tered ion balances created in the previous stage. At this stage, organ systems fail and the organism can die.

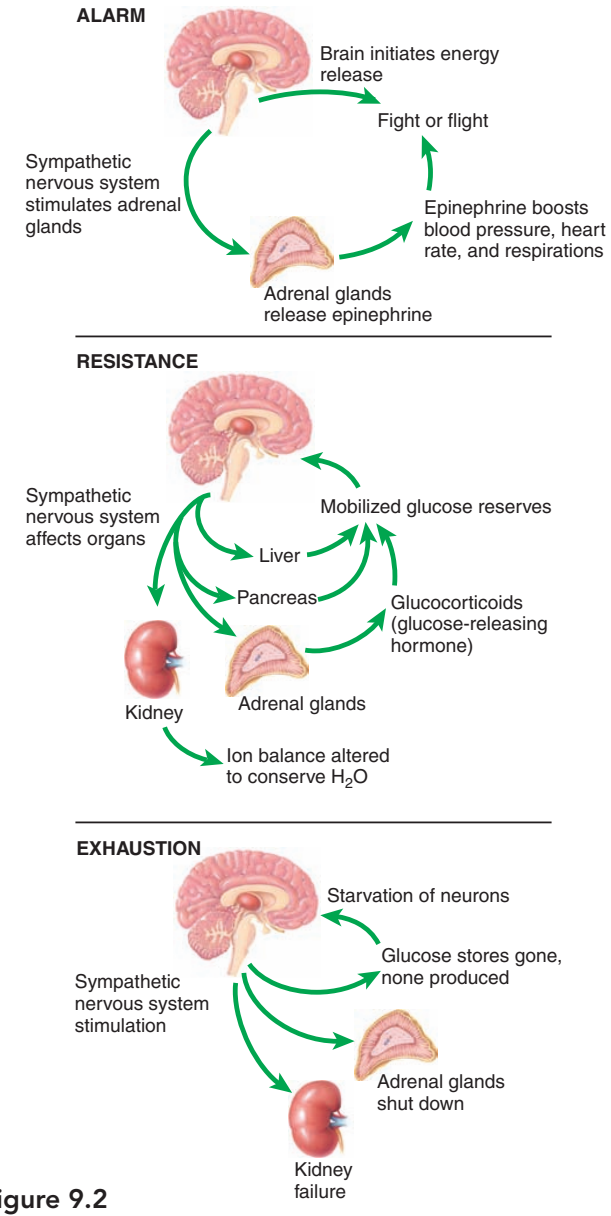


Figure 9.2

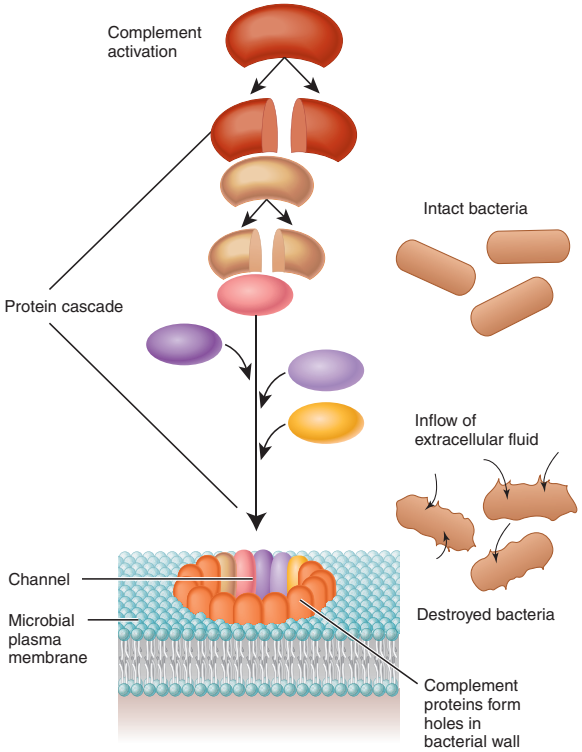
2 Skin and Mucous Membranes Are the First Line of Defense 216

- The skin is composed of the stratified squamous cells of the **epidermis** and underlying connective tissues of the **dermis**.
- Hair, nails, and glands are accessory organs. Sensory structures in the dermis detect pressure, temperature, and pain. Glands secrete either oils or sweat onto the surface of the skin and hairs. The sweat glands help maintain thermal homeostasis. Nails and hair serve protective functions.
- Mucous membranes provide nonspecific immunity in cavities open to the exterior, including the mouth, digestive tract, respiratory tract, urinary tract, and reproductive tract. Mucus, secreted by the epithelial cells of the membranes, retards **pathogens** on mucous membranes.

3 We Have a Second Line of Inmate Defense 221

- As shown here, the complement system fights bacteria by destroying their cell walls. **Interferon**, secreted by cells that are infected by a virus, is a chemical warning that helps nearby cells prepare for viral invasion.

Figure 9.10



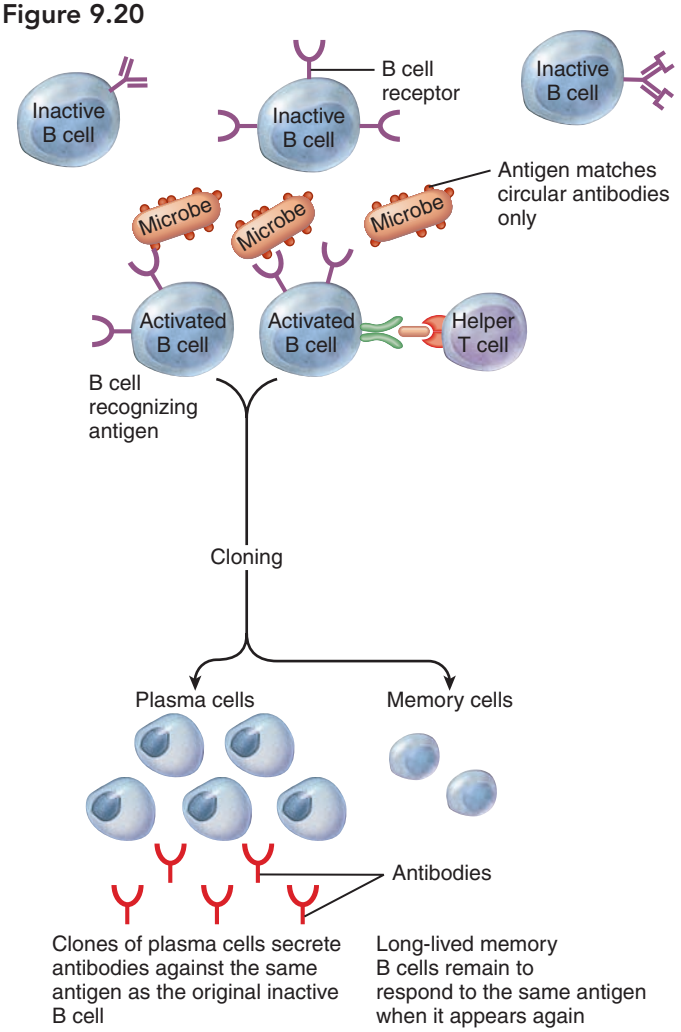
- Fever raises the body temperature so that chemical reactions will act more quickly, and it is therefore effective against a wide range of threats. Inflammation is a series of reactions that allow more blood to reach the site of infection to help with tissue repair, block the entry of more pathogens, and slow the spread of pathogens. **Phagocytes** are cells that remove circulating pathogens, as well as any cellular debris created during infections.

4 The Lymphatic System and Specific Immunity Are Our Third Line of Defense 224

- The **lymphatic system** returns interstitial fluid to the cardiovascular system, absorbs and transports fats, and provides specific immunity. The system is composed of lymphatic organs, lymphatic tissue, and lymphatic vessels. Lymph forms when portions of blood are forced through the capillary wall. This lymph fluid bathes and cleans the tissues.

- Cell-mediated immunity is embodied in **lymphocytes** in the bloodstream and lymph nodes. Antibody-mediated immunity is carried out by B cells residing in the lymph nodes, as shown in this diagram. Helper T cells detect a specific antigen and stimulate the proper B cell. That B cell then clones, producing plasma cells and memory cells. The plasma cells produce antibodies against the specific antigen. There are five classes of antibodies, on the basis of shape and timing of appearance. When the pathogen has been cleared, memory cells lie in wait for a second invasion by the same pathogen.

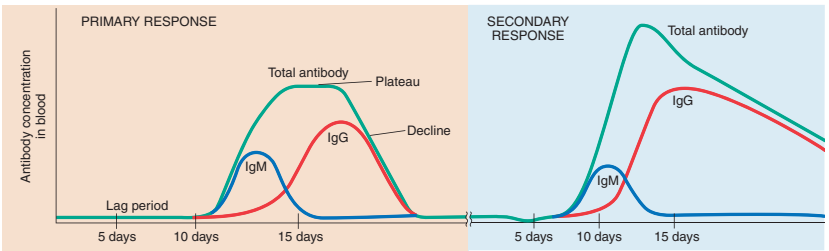
Figure 9.20



5 Immunity Can Be Acquired Actively or Passively 236

- Active immunity refers to immunity obtained through activating your immune system and creating memory cells. Both immunizations and the natural course of recovering from disease cause a population of memory cells to form in the body. When the same antigen reappears, the memory cells immediately clone and eliminate the antigen. This secondary response is far faster than the primary **immune response**, as shown in the chart below.

Figure 9.24



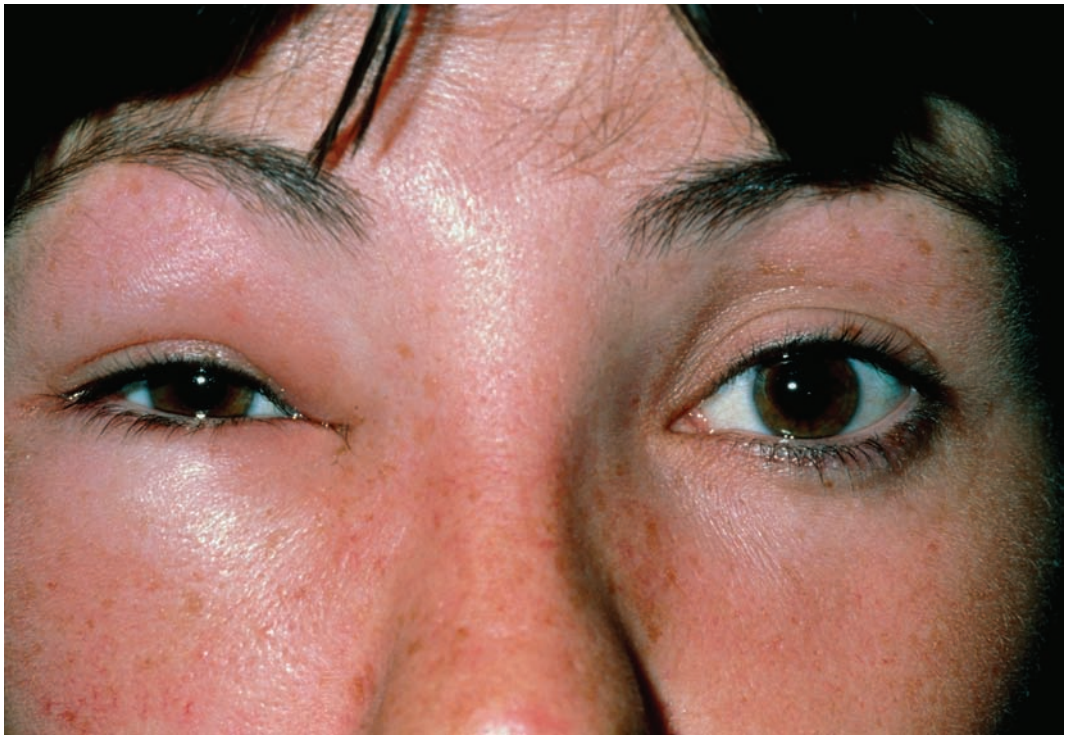
- Passive immunity occurs when **antibodies** are given to an individual rather than formed by that individual. Natural passive immunity occurs when a fetus or infant receives antibodies from the mother, through diffusion across the placenta and then via breast milk.

Key Terms

- agglutinate 231
- antibodies 229
- apoptosis 231
- attenuated 231
- cytokines 234
- cytotoxic T cells 233
- dermis 216
- epidermis 216
- epinephrine 214
- follicle 220
- interferon 212
- immune response 224
- immunization 229
- interstices 225
- keratinized 220
- lymphatic system 224
- lymphocytes 229
- melanocytes 217
- mesenteric 227
- nociceptors 218
- open system 227
- pathogen 212
- phagocytes 212
- stem cells 229
- titer 236

Critical and Creative Thinking Questions

1. Marie sat quietly in the back of the class feeling relaxed, even though this was her first college class. “Here goes; this is the beginning of my future,” she excitedly thought. As the teacher walked to the front of the room, Marie suddenly felt dizzy and broke into a cold sweat. What was happening to her? What is the natural course of these events?
2. Swimming in the ocean may expose a bather with an open wound to staphylococcus infection. What characteristics of the skin normally prevent these infections? How does an open wound compromise these defenses?
3. Suppose you lacked all innate or nonspecific defenses. First, list exactly what you would be missing. Second, for each item, describe how life would be different without that mechanism. For as many of the listed items as possible, describe some behavioral changes that would promote your survival.
4. Rheumatoid arthritis is an autoimmune disease. In autoimmune diseases, your immune system loses its ability to differentiate self from nonself and begins to attack your body. In rheumatoid arthritis, the attack affects cartilage in the joints. Using what you have learned about the immune response, what symptoms would you predict? How would the normal functioning of the immune system lead to these symptoms? What might a physician prescribe for rheumatoid arthritis?
5. **CLINICAL CLICK QUESTION**
   It is late spring, and as the pollen count in the air increases Bonnie is preparing for her usual seasonal maladies. She purchases over-the-counter antihistamines, eye drops, and even some throat lozenges. What immune disorder does Bonnie suffer from? She understands that her seasonal troubles are triggered by increased pollen in the air, as her immune system recognizes that pollen in a pathogen that it must destroy. This year, however, Bonnie found herself in a dangerous situation. During a long walk through a field of fragrant clover, Bonnie was already having trouble breathing. Without warning, a bee stung her on the arm. Almost immediately Bonnie’s blood pressure dropped, causing dizziness. Her pulse rate sky rocketed, but was weak and difficult to monitor. Her breathing got more difficult as her airway narrowed, and she could not continue walking. What was happening to her? Why were these symptoms occurring so quickly? Could this be a life-threatening situation for her? To answer these questions, and learn more about this common severe allergic reaction, visit the Mayo Clinic site, http://www.mayoclinic.com/health/anaphylaxis/DS00009.



What is happening in this picture?

Depending upon your personal choices, you may look upon a scene like this and remark on the bravery of the individual and the artistry of the tattoo itself, or you may worry about the health implications of what you see. A tattoo is created by implanting small bits of pigment under the epidermis, into the dermis. Nowadays, the pigment particles are placed under the epidermis using a sterile needle, but traditional methods using animal quills and sharpened bits of bone are still practiced in some cultures. Inserting the pigment through the epidermis into the dermis damages both tissues and stimulates an immune cell response.

NATIONAL GEOGRAPHIC

Think Critically

1. What type of immune response does the introduced ink initially stimulate?
2. How does the migration of phagocytes into the newly tattooed area affect the pigment particles?
3. Why do tattoos fade with time? (What is happening to the pigment particles?)

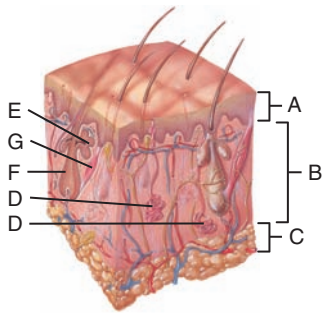
Self-Test

1. Which of the following can be classified as stressors?
   a. eating a heavy meal
   b. coming down with strep throat
   c. beginning a new college semester
   d. All of the above are stressors.

2. Innate immunity includes all of the following EXCEPT _____.
   a. the skin and mucous membranes
   b. phagocytes
   c. antibodies and immune cells
   d. the complement system

3. The phase of the General Adaptation Syndrome that begins with a large dumping of epinephrine into the system is _____.
   a. the alarm phase
   b. the resistance phase
   c. the exhaustion phase
   d. All of the phases include dumping epinephrine.

Questions 4 and 5 relate to this figure.



4. Identify the structure labeled B on this diagram.
   a. epidermis
   b. hypodermis
   c. dermis
   d. adipose tissue

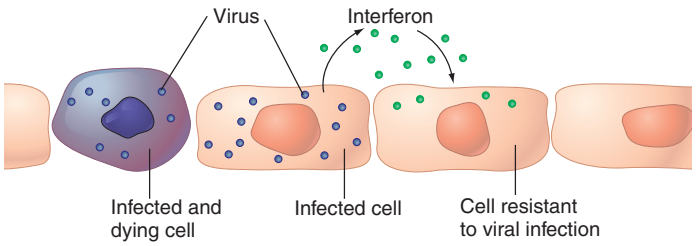
5. Which structure is directly responsible for thermal homeostasis?
   a. A
   b. C
   c. D
   d. G

6. The function of melanocytes is to _____.
   a. produce keratin
   b. maintain internal temperature
   c. produce dark pigments to absorb light
   d. store energy for later use

7. Oil glands are located everywhere on the skin, including the face and lips.
   a. True b. False

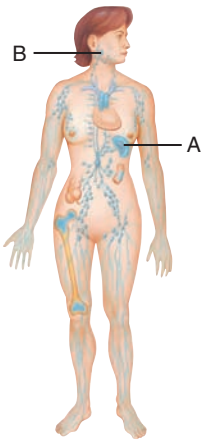
8. The chemical defense that destroys bacteria is called _____.
   a. immunity
   b. the complement system
   c. interferon
   d. phagocytosis

9. The type of innate defense against pathogens seen in this figure is _____.
   a. inflammation c. interferon
   b. fever d. phagocytosis



10. The lymphatic system is anatomically similar to the circulatory system, with a series of vessels that transport lymph to and from the heart.
   a. True b. False

11. Identify the structure indicated as A on the diagram.
   a. lymph node c. Peyer's patch
   b. tonsil d. spleen

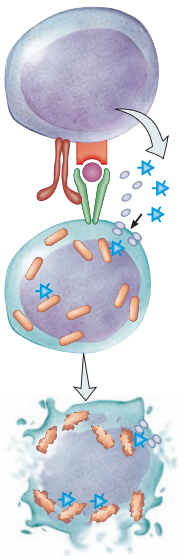


12. Humoral immunity employs _____.
   a. T cells
   b. B cells
   c. antibodies
   d. All of the above are correct.

13. Specific immunity requires cells to demonstrate specificity, memory, and self-recognition.
   a. True
   b. False

14. The type of T cell that binds an antigen, clones to amplify the signal, and then stimulates the B cell that will produce the matching antibody is the _____.
   a. natural killer T cell
   b. thymic cell
   c. APC cell
   d. helper T cell

15. The type of immune cell causing the reaction seen here, where the pathogenic cell is attacked by released perforin, is the _____.
   a. helper T cell
   b. cytotoxic T cell
   c. HLA cell
   d. antigen-presenting cell



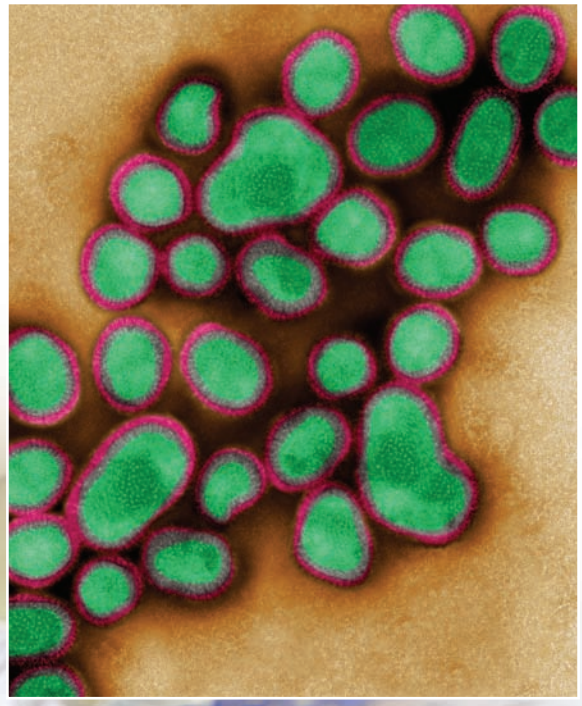
THE PLANNER

Review your Chapter Planner on the chapter opener and check off your completed work.

10 Infectious Disease and Epidemiology

H1N1, or swine flu, suddenly burst onto the international scene in mid-2009. Newspapers were carrying stories of entire villages in Mexico succumbing to this flu, with many patients dying. The first confirmed case of H1N1 in the United States was identified by the Center for Disease Control (CDC) on April 15, 2009. New patients were confirmed almost daily thereafter, and it became obvious that this flu was able to spread from person to person—a requirement for phase 4 pandemic. By June 11, 2009, World Health Organization declared this strain of flu to be a new virus, and raised the worldwide pandemic alert level to phase 6, indicating widespread human infection. The rapid spread of this virus, along with the sheer number of cases being reported across the United States, caused the U.S. government to declare a public health emergency.

Although the news media took this to mean that the threat of dying from H1N1 was high, most people in the United States who became ill recovered without requiring medical attention. What it really meant was that the disease was spreading quickly, and seemed uncontrollable. Even before the end of June, every one of the 50 states reported cases of H1N1. Although the Northern Hemisphere flu season typically ends with the advent of summer, U.S. cases continued to be reported, with some areas indicating increases in number through July and August 2009.



CHAPTER OUTLINE

The Study of Epidemics Is Global in Scope 246

- Epidemiologists Apply the Scientific Method to Epidemics and Pandemics
- Infectious Disease Is a Global Issue
- The Disease Process Has Several Stages

Bacteria Are Single-Celled Wonders that Can Cause Disease 251

- Bacteria Are Small Yet Successful
- Bacteria Are Classified by Shape, Staining, and Genetics
- Antibiotics Kill Bacteria
- Several Infectious Diseases Are Bacterial in Origin

Viruses Can Reproduce and Kill, but They Are Not Alive 258

- Most Epidemics Are Caused by a Virus

AIDS and HIV Attack the Immune System 265

- To Understand Is to Protect
- HIV Targets the Helper T Cell
- HIV Treatment Remains an Uphill Battle, and Vaccines Are Hard to Make
- Pandemics May Force a Change in Familiar Social and Economic Arrangements

Other Pathogens Carry Other Dangers 270

- Fungi Are Eukaryotic Organisms that Play a Major Role in Decay Processes
- Protists Include Unicellular Organisms
- Prions Are Misshapen Proteins

CHAPTER PLANNER

- ❑ Study the picture and read the opening story. Scan the Learning Objectives in each section: p. 246 ❑ p. 251 ❑ p. 258 ❑ p. 265 ❑ p. 270 ❑
- ❑ Read the text and study all figures and visuals. Answer any questions.

Analyze key features

- ❑ I Wonder..., p. 250
- ❑ Biological InSight, p. 253 ❑ p. 259 ❑
- ❑ What a Scientist Sees, p. 254
- ❑ Ethics and Issues, p. 255
- ❑ Process Diagram, p. 260 ❑ p. 267 ❑
- ❑ Health, Wellness, and Disease, p. 269
- ❑ Stop: Answer the Concept Checks before you go on: p. 250 ❑ p. 258 ❑ p. 265 ❑ p. 270 ❑ p. 272 ❑

End of chapter

- ❑ Review the Summary and Key Terms.
- ❑ Answer the Critical and Creative Thinking Questions.
- ❑ Answer What is happening in this picture?
- ❑ Answer the Self-Test Questions.

10.1 The Study of Epidemics Is Global in Scope

LEARNING OBJECTIVES

1. **Define** "epidemic" and give two examples from history.
2. **Relate** the scientific method to the study of epidemics.
3. **Explain** the importance of disease surveillance.
4. **Describe** one major program of WHO.
5. **Describe** the stages of the disease process.

When we hear the word "epidemic," what comes to mind? For many who have studied history, the word invokes stories of the black plague. Others are reminded of the 1918 Spanish flu that took the lives of an estimated 20 to 50 million people, including some 675,000 Americans. Still others think of AIDS. These are frightening examples of the devastating ability of a disease running unchecked through the human population. The definition of an **epidemic** is just that: it is a disease that affects many individuals at once, spreading rapidly via infection from one person to the next in an area where the disease is not permanently or traditionally found. An epidemic becomes a **pandemic** when a very large number of people are affected, over a very wide geographic area—usually the entire globe.

History includes many epidemics and pandemics, often with far-reaching consequences. Were it not for small pox, yellow fever, mumps, and measles, the conquest of the Americas by Europeans may have proven to be a much harder feat. Even the settling of North America was facilitated by epidemics that spread through the native populations—epidemics begun by diseases brought in with the invading parties. An entire research **paradigm** has been founded around the importance of epidemics and pandemics in history, exemplified by the book, *Guns, Germs, and Steel,* written by Jared Diamond in 1997. In this book, Diamond argues that the transmission of disease and the spread of epidemics has as much to do with cultural domination as the development of weapons and advanced civilization.

paradigm A model or pattern; a way of seeing a situation based on cultural assumptions, concepts, and values.

Epidemiologists Apply the Scientific Method to Epidemics and Pandemics

It is imperative that we as a worldwide population understand how past epidemics got started and what allowed them to continue to their destructive end. Methods used to study epidemics include case studies, case control studies, **cohort** studies, and outbreak investigations. In essence, epidemiology is the application of the scientific method to the field of disease. Epidemiologists first observe the disease process, then they hypothesize the origin of the disease and who is most susceptible. Once they have an accepted hypothesis, they undertake a controlled study, collect data, and analyze the results. Communication of these results is essential, as the goal of epidemiology is to stop the current epidemic and prevent its return.

cohort A group of organisms sharing a particular characteristic.

As mentioned above, case studies are one tool of the epidemiologist. These studies are in-depth analyses of the experiences of one particular patient or a group of related patients. Case studies may lead to hypotheses about the cause or treatment of a disease. A complete medical interview is part of every case study, and it is usually carried out by a medical professional, as in Figure 10.1.

If a hypothesis is generated from the information gleaned from case studies, a case control study may ensue. In that situation, a group of patients with similar histories

Medical professional • Figure 10.1

Doctors and other medical professionals put the scientific method into practice each day, observing, forming hypotheses, gathering data, and in some cases asking for more medical tests to gain more data.

A sample group • Figure 10.2

Epidemiologists try to avoid selection bias by including a wide range of profiles.

are solicited from the original population; all of the people in this group are at a similar stage of the disease. These people are questioned about their contact with the original case studied, as well as their history prior to and immediately after showing symptoms of the disease. Case control studies shed light on the method of infection, providing the first real clues needed to halt the spread of the disease.

Once the method of disease spreading is determined, a cohort study may begin. In this phase of the research, participants are chosen from the infected area. These people should be disease- and symptom-free at the beginning of the study, and they should have a common element. For example, a cohort may consist of smokers, postmenopausal females, schoolteachers, or college students. The participants are monitored for signs of the disease in order to estimate the likelihood of people within certain subpopulations getting sick.

Sudden appearance of disease is called an outbreak. The sudden appearance of a disease in a small, localized group of people is called an outbreak. When an outbreak is identified, scientists and public health officials immediately spring into action. The investigation that follows includes verifying the diagnosis, defining the symptoms of the disease, hypothesizing about the cause of the outbreak, collecting data to support or refute that hypothesis, developing controls and preventative measures to stop the outbreak from infecting larger areas, and finally communicating the findings to the greater population. If these steps sound familiar, they should! Outbreak investigation is a practical application of the scientific methods discussed in Chapter 1.

The study of epidemics is fraught with error. It is difficult to group people into categories, as we all have slightly different physiologies. **Figure 10.2** gives some indication of the many subtle differences that exist in a group of us. Something as simple as the type of foods we prefer or the hours of sleep we usually obtain may make a difference in our tolerance to a specific pathogen. Not only do we have physiological differences, but we also exhibit differences in our lifestyle choices and our **socioeconomic level**. Those with more privileges may be able to afford better overall health care, live in more sanitary environments, and eat healthier foods than those less fortunate. All of these differences can be sources of error in studying epidemics.

socioeconomic level The relative position of an individual within the larger population in terms of social and economic factors.

Other sources of error in epidemiology studies include random error introduced due to sampling variability, systemic error due to using equipment with differing sensitivities or technicians inaccurately recording the data collected, and selection bias when participants are not chosen properly. Imagine how much more difficult it would have been to identify the link between deer ticks and Lyme disease if the epidemiologists performing the study inadvertently left out individuals with regular outdoor activities. The epidemiologists are biased toward those individuals that fit the profile they have created for the disease being studied. This again may cause the scientists to miss a vital link in the pathology of the epidemic.

Infectious Disease Is a Global Issue

Although our bodies have an excellent series of defenses against disease, epidemics still occur. Because epidemics can cross borders, combating them requires international

leadership. Since 1948, the World Health Organization (WHO) has been the branch of the United Nations dedicated to helping people attain higher levels of health. One of the goals of WHO is to provide medical care to rural populations, such as the clinic in **Figure 10.3**. The policies of this organization are designed to enhance quality of life through improvements in physical, mental, and social well-being.

In collaboration with national health organizations, such as the U.S. Centers for Disease Control and Prevention, WHO tries to keep tabs on epidemics. Researchers from WHO constantly model the spread of epidemics in an attempt to stay ahead of and predict viral outbreaks. WHO helps transfer samples of new diseases to safe labs where they can be quickly identified.

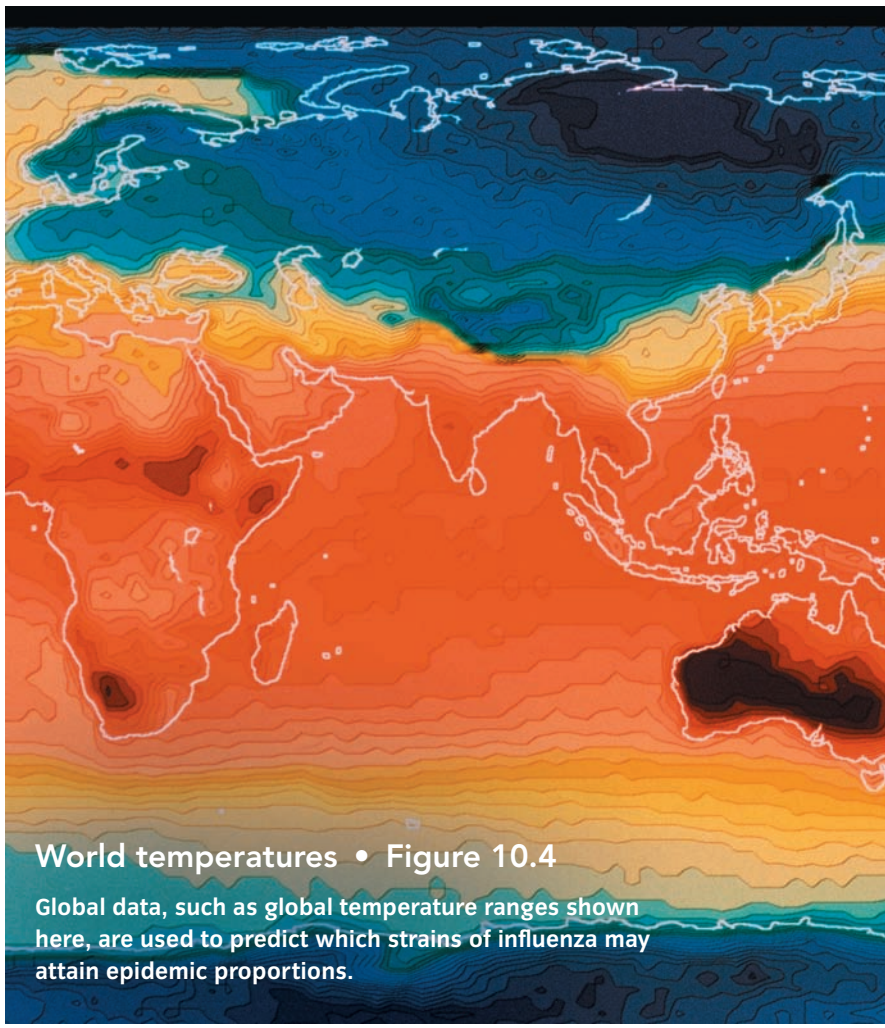
WHO also helps predict which strains of influenza (the "flu") are most likely to appear among humans each winter. Their predictions are based on past influenza strains and on hypotheses of the ways changing environmental conditions may affect the competitive advantages of particular strains. Data, such as the map of world temperatures in **Figure 10.4**, helps WHO in their predictions. On this basis, the organization then selects which antigens to include in the "flu shot," and corporations and national medical systems make and administer the shots to at-risk individuals.

Several diseases are on WHO's list of most dangerous epidemics. They list the following diseases as threatening outbreaks: Rift Valley fever, monkeypox, Nipah virus, and plague. The first three of these frightening epidemic diseases are viral, whereas plague is caused by a bacterium.

Another world health concern is HIV and the resulting AIDS epidemic caused by that virus. Common influenza remains a deadly nuisance, but smallpox was one of the greatest killers in history. At the end of the twentieth century, WHO directed a worldwide campaign to eradicate smallpox, the only viral disease ever successfully eradicated from the human population. Smallpox is a very infectious, sometimes fatal viral disease that causes raised pustules to develop first in the mouth and then over the entire body. These bumps eventually pop, releasing viral particles and causing pitting of the skin. WHO is now in the midst of a campaign to eradicate polio, which attacks the motor neurons of the brain stem and spinal cord and causes paralysis in 1 of 100 cases. Smaller programs include steps to eradicate tuberculosis and measles. Although not currently on the "top 5" list of potential outbreak candi-

A rural clinic in Nicaragua • Figure 10.3

World Health Organization provides vaccines for patients in developing countries as part of their effort to eradicate crippling diseases. Often, these vaccines are given in free health clinics, such as this one.



World temperatures • Figure 10.4

Global data, such as global temperature ranges shown here, are used to predict which strains of influenza may attain epidemic proportions.

dates, tuberculosis, plague, and leprosy are all bacterial diseases that have reached epidemic proportions. To read about the latest epidemic concerns, see *I Wonder… Are Any Epidemics Occurring Right Now?* on the next page.

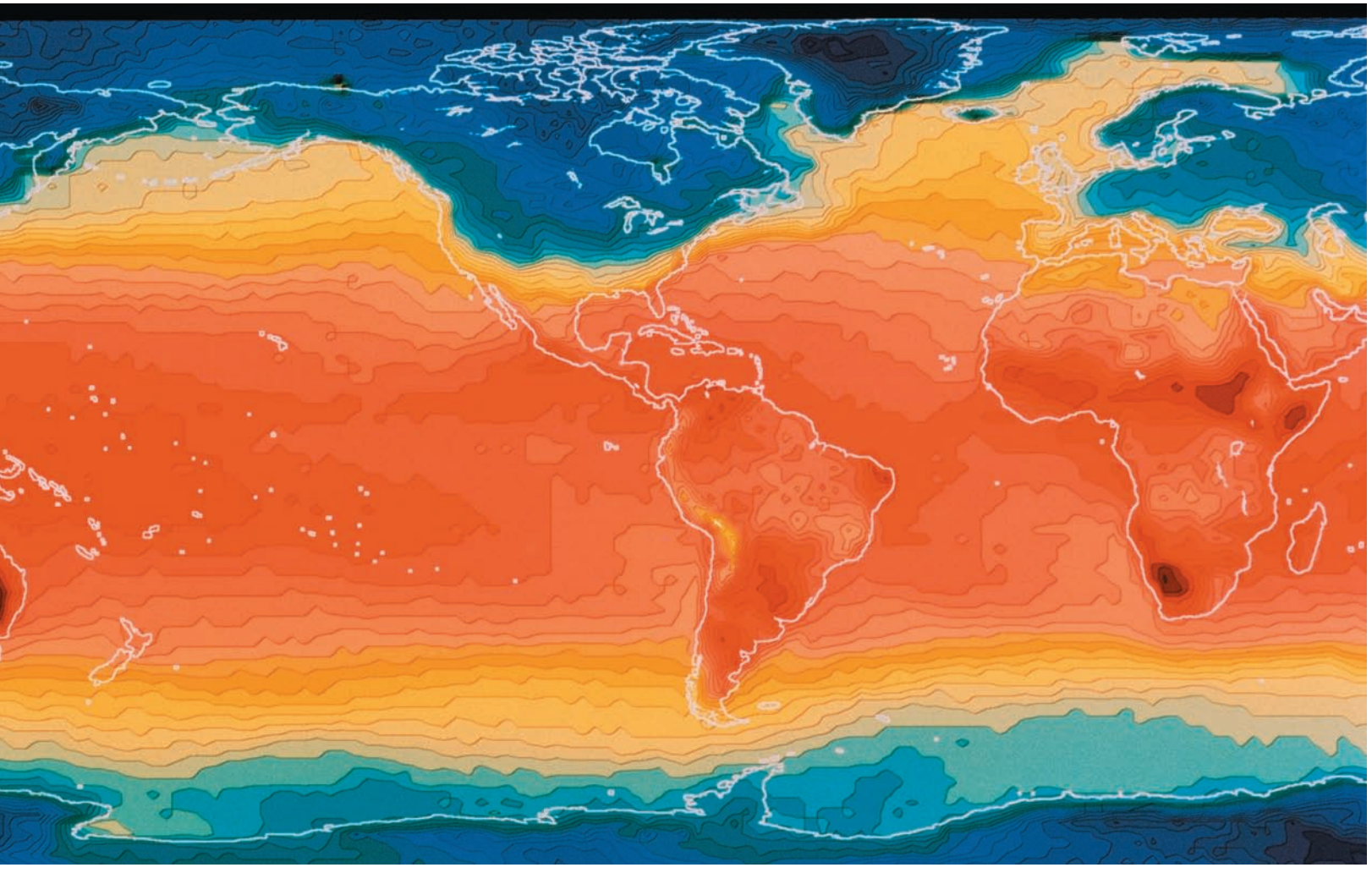
Although our bodies are wonders of natural science, we often need help in maintaining our health. Our lifestyle necessitates that humans live in close contact with one another. Unless this changes, we will always be faced with new viral and bacterial threats to our population's continued health. In many cases, the best thing we can do to protect ourselves is wash our hands thoroughly and often!

The Disease Process Has Several Stages

Like all diseases, epidemics begin with a simple process: The pathogen enters the human body (or host) and alters the physiology of that body to ensure its own survival, in turn causing discomfort and possibly death as a result.

Entry into the host occurs through a specific mode of transmission. Pathogens can be transmitted via physical contact with an infected person, contact with airborne pathogenic particles, or direct injection of the pathogen into the body. Ebola virus, for example, is transmitted from one person to another through direct contact with the live virus on the tissues or skin of a patient. It can then migrate to the mucous membranes of the second person and infect him or her. Tuberculosis is small enough to travel in airborne droplets, and when inhaled into the lungs of another person it will begin another infectious cycle. Dengue fever, malaria, HIV, and chikungunya fever are all transmitted via direct contact with the host's blood supply.

Once in the body, each pathogen causes a specific series of symptoms. Bacterial infections can cause disease by adhering to host cells, colonizing host tissues, or even inhibiting the host's typical immune responses. Viruses often invade and take over host cells, as discussed



I WONDER...

Are Any Epidemics Occurring Right Now?

There are some diseases that cause continual problems for humans—notably cholera, dysentery, meningitis, typhoid fever, and hepatitis. WHO lists each of these as epidemic in some countries on an almost continuous basis. Of these, the most common is cholera. This disease has reached epidemic proportions in Benin, Burundi, Cameroon, Equatorial Guinea, Kenya, Malawi, Mozambique, Liberia, Zambia, and Zimbabwe. Elsewhere, diabetes, syphilis, HIV/AIDS, tuberculosis, and hepatitis C are listed as epidemic. Both diabetes and hepatitis C exist in epidemic proportions in developed nations, including the United States.

A relative newcomer to the list of current epidemics is chikungunya, a fever. This disease is caused by a virus that is transmitted to humans by the bite of an infected mosquito. Initially, it causes the same symptoms as dengue fever, another mosquito-borne disease. The patient suffers fever, headache, nausea, vomiting, muscle pain, and rash. The worst symptom of chikungunya is the joint pain it causes, which is similar in intensity to the pain caused by arthritis and just as debilitating. The joint pain can last for weeks or months.

Because epidemiologists have identified the mosquito as the carrier of yet another epidemic, scientists are working to eradicate the pest. In the meantime, a good way to protect yourself is to drain all stagnant water from your lawn and wear mosquito repellent when you are in areas where mosquitoes are known to live.

later in the chapter. Viral infection requires that the host cells exhibit virulence factors—specific proteins that the viral particle can bind to. Humans do not have the same complement of proteins on their cells as other organisms do. If the virulence factor necessary for a specific viral invasion is lacking, the virus will not be able to attack those cells. The presence or absence of virulence factors thus determines susceptibility to viral infection. Most viruses are species specific because of this requirement.

Whether bacterial, viral, or protozoan in origin, many pathogens produce toxins that cause illness. Food poisoning, for example, is caused by toxins produced by the infecting bacteria.

Finally, age has an effect on the severity of any disease. Very young people do not have a well-developed immune system to combat illness, nor do they usually have the energy reserves to sustain themselves through a prolonged illness. The elderly also have a slower immune response and fewer reserves to draw upon in times of crisis.

CONCEPT CHECK

1. **What** is an epidemic, and **what** are two examples of an epidemic from history?
2. **How** is the scientific method used to study epidemics?
3. **Why** is disease surveillance important?
4. **What** is the extent of WHO's involvement in the yearly flu shots?
5. **What** are the stages of the disease process?

10.2 Bacteria Are Single-Celled Wonders that Can Cause Disease

LEARNING OBJECTIVES

1. **Define** prokaryotic and eukaryotic.
2. **Outline** the structure of a typical bacterium.
3. **Describe** the function of antibiotics.
4. **List** five bacterial pathogens.

The human species has been combating viral, bacterial, and parasitic invasions for millions of years. According to *Bergey's Manual*, the premier resource on the classification of bacteria, it is estimated that there are between 2 and 3 billion bacterial species on the Earth, but only a select few of these (less than 0.5%) cause human disease. Some of our most troublesome diseases are viral, but there are also bacterial diseases that are very difficult, if not impossible, for us to control. A relative newcomer to the pathogenic stage is the prion, an oddly shaped protein that is the causative agent of mad cow disease. Each class of pathogen has distinctly different characteristics, and each requires different treatments to overcome.

Throughout this chapter, we will discuss viral and bacterial infection. It is important to recognize the differences between these two categories of pathogens. The differences emerge from the fact that one is a true cell, whereas the other is a bit of protein surrounding a few genes.

Bacteria Are Small Yet Successful

prokaryotic Type of single-celled organism with no membrane-bound organelles, usually having only genetic material as organelles.

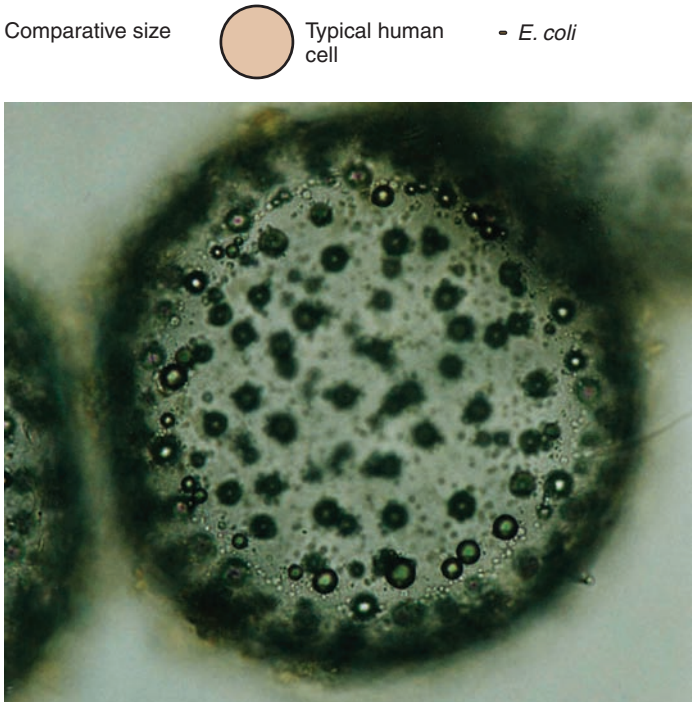
Bacteria are **prokaryotic** cells that can be found in the ground, in the water, even in the air, not to mention inside humans and our fellow animals. Bacteria are generally smaller than eukaryotic cells, ranging in size from the 100-nanometer mycoplasma to the average-sized 7-micron cyanobacterium. A bacterial giant was recently discovered in the seafloor off Namibia. *Thiomargarita namibiensis*, as seen in **Figure 10.5**, means "sulfur pearl of Namibia." It was discovered in 2000 by Dr. Andreas Teske of Woods Hole Oceanographic Institute. This spherical bacterium is roughly the size of a period in a 12-point font. (Most bacteria are barely visible with a light microscope.)

Like all prokaryotes, bacteria have no internal membranes, no division of labor, and no specialized area where DNA is stored. Any special function, such as **photosynthesis**, is carried out by the cell membrane. Bacteria do have one organelle in common with eukaryotic cells, however. Bacterial cells transcribe and translate DNA just like eukaryotes, so they have ribosomes in their cytoplasm. These ribosomes are so similar to those in eukaryotic cells that some scientists think all cells may have a common origin.

photosynthesis Process of producing carbohydrates with sunlight, chlorophyll, carbon dioxide, and water.

Thiomargarita namibiensis cell • Figure 10.5

T. namibiensis is visible to the human eye. It can grow so large because it fills its center with a nitrogen-containing vacuole. Nutrients and waste are diffused between the cell membrane and the exterior and between the central vacuole and the bacterial cytoplasm.



Bacteria Are Classified by Shape, Staining, and Genetics

Being relatively simple organisms, bacteria were traditionally classified by shape and by the staining patterns of their cell wall. We have added a third way that classifies bacteria by their genetics, not their appearance.

Bacteria are either rod-shaped or spherical. The shape of bacteria falls into two broad categories: spherical and rod-shaped. Terms for spherical bacteria include *cocci* for single spherical bacteria, *streptococci* for those that live in chains, and *staphylococci* for those that grow in large masses. Bacilli (singular: *bacillus*) are rod-shaped cells that can be oval, tapered, or curved. Spirochetes are long rod-shaped bacterial cells that twist about their long axis. The bacterium that causes Lyme disease is an example of a spirochete. See **Figure 10.6**.

Bacteria are either gram-positive or gram-negative. Gram stain, the most common bacterial staining technique, was developed by Hans Christian Gram to distinguish two types of bacterial infections in the lungs. Bacteria are either gram-positive or gram-negative. Gram-positive bacteria retain a purple color from the Gram stain, whereas gram-negative bacteria pick up a red dye, safranin, in the Gram staining process. *Staphylococcus aureus* (staph infections) and *Streptococcus pneumoniae* (strep infections) are both gram-positive, whereas *Escherichia coli* (*E. coli*) is gram-negative.

Bacteria can be classified by their genetics. A third, more precise, way to classify bacteria reflects their genetics, not their appearance. Two bacterial strains can be compared at the level of their DNA bases with DNA–DNA hybridization. This technique searches the bacterial DNA molecules for areas of identical base pair series. The more similarities there are between two bacterial strains, the more closely they are related. In this way we measure how closely the DNA of one species resembles the DNA of another. Alternatively, a study could focus on a particular common gene that changes slowly through time. Additionally, scientists can look at similarities and differences in ribosomal RNA; in fact, a sub-branch of this investigation, called 16S RNA, has been used to track the evolutionary relationships of the entire tree of life, not just bacteria.

Humans live with more than 2,000 types of bacteria. If you could count the bacteria in your digestive tract, you would find that their number exceeds the number of cells in your body. Scientists estimate that if you have 10 quadrillion cells in your body, you may have as many as 100 quadrillion bacterial cells! Your mouth probably houses more than 400 species of bacteria all by itself. Clearly, most of these bacteria are harmless or even helpful. Bacteria in your gut, to take just one example, produce vitamin K, which is essential in blood clotting. Without bacteria in your body, you would die. Before you spend money on antibacterial soap or cleanser, consider that most of the microbes you encounter are harmless, helpful, or easily controlled by your innate and adaptive defenses.

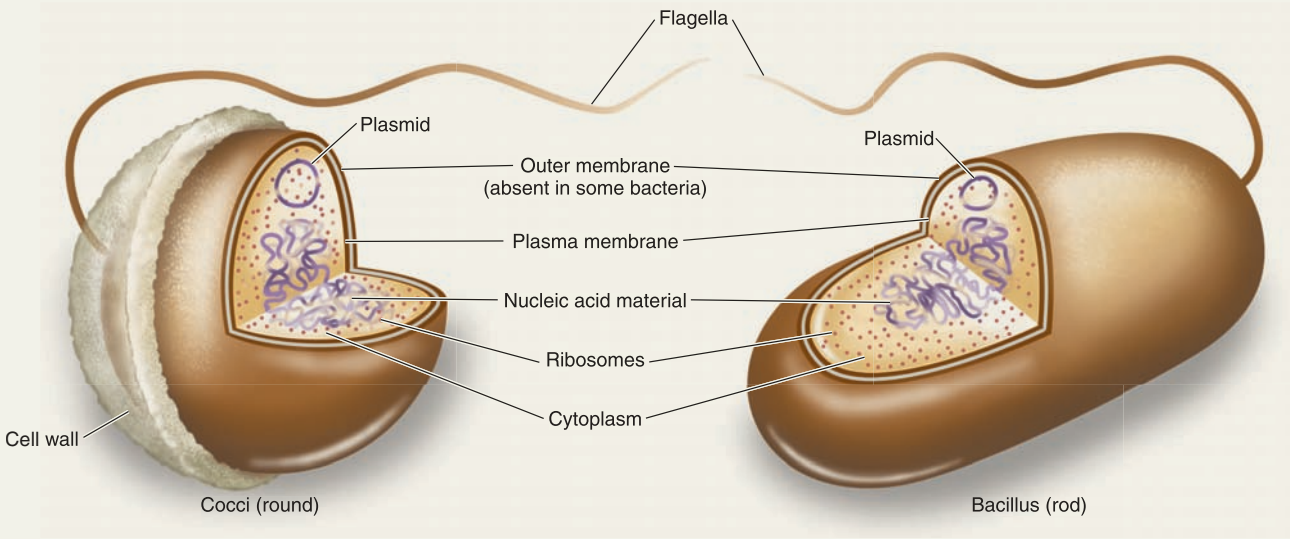
Antibiotics Kill Bacteria

When we need to kill bacteria, we turn to antibiotics, drugs that interfere with cellular processes that bacterial cells undergo every day. Various antibiotics prevent protein synthesis by binding to bacterial ribosomal RNA; others destroy essential metabolic pathways; and still others block DNA and RNA synthesis. Antibiotics also affect cell walls, which are found in bacteria but not in mammals, either breaking them down or preventing new cell walls from forming.

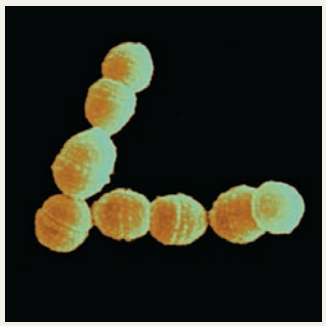
Fortunately, bacteria respond to antibiotics, and we have a host of different classes of antibiotics to choose from. These compounds destroy the bacterial cells by altering their ability to complete physiological processes, and therefore are usually effective at eradicating the bacterium. Once treatment is begun, the patient feels better relatively quickly. Recently, however, strains of bacteria resistant to our known antibiotics have been appearing in certain settings. Thus far, these resistant strains are isolated to a few pockets of infection in hospitals in major metropolitan areas. Hopefully, we will be able to identify new antibiotics that will allow us to continue to effectively treat these newly resistant bacterial diseases. Scientists are constantly testing for new antibiotics, as shown in *What a Scientist Sees: Testing Antibiotics* on page 254.

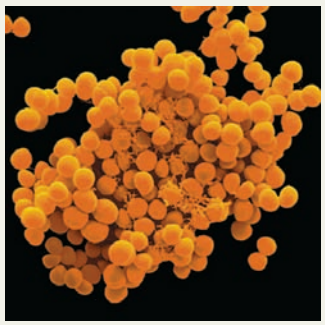
How do bacteria become resistant to antibiotics? Bacteria have fiendishly clever defenses against antibiotics. Although bacteria sometimes mutate with the result that they become resistant to antibiotics, more commonly they acquire a resistance gene from bacteria already carrying it. This antibiotic resistance is developing into a serious problem, as bacteria are rapidly becoming immune to many modern antibiotics. One gene, or a ring of

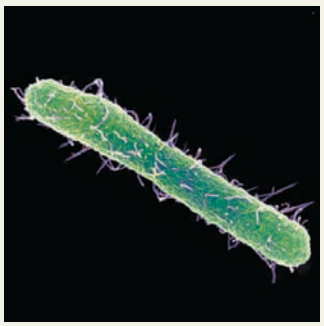
The bacteria that cause human disease are prokaryotic organisms classified in the domain *Eubacteria*. Although their shapes vary from round to rod-shaped or even spiral, they all have some common features. Bacteria have no internal membranes, but do carry ribosomes and nucleic acid within the confines of their membranes. Most bacteria also carry a small circular bit of DNA called a plasmid. This plasmid carries extra genes that assist in survival, such as antibiotic resistance. Bacteria are able to share plasmids by touching membranes and allowing the plasmid to flit across, spreading these extra genes through a population quickly. This sharing can even occur between bacteria of different species.




Cocci


Streptococci


Staphylococci


Bacillus


Bacillus


Spirochetes

WHAT A SCIENTIST SEES

Testing Antibiotics

Bacterial cultures are grown from samples of the bacteria found in patients of an epidemic. Agar plates are "seeded" with the bacteria and placed in an incubator. The bacterial population will increase exponentially until the entire agar plate is covered with a continuous lawn of bacteria. The susceptibility of this bacterium to antibiotics can then be tested by dropping small paper discs soaked in various antibodies on the lawn. Those that will be effective against the bacterium will form a clear patch in the otherwise continuous lawn. The more effective the antibiotic, the larger will be the cleared circle surrounding the disc. Some antibiotics are not effective at all, while others cause large areas of bacterial inhibition. Using this information, scientists can recommend successful antibiotic treatment for the epidemic, usually suggesting a combination of antibiotics.

Think Critically

1. Why are there clear areas around each of these paper discs?
2. Which paper disc holds the most effective antibiotic?
3. Can you design a scientific experiment using this technique to help identify the cause of an epidemic?

genetic material including a few genes, may carry resistance to several antibiotics, and it may be transferred from one species of bacterium to another, not only among bacterial cells of a single species. Bacteria can become resistant to specific antibiotics through several mechanisms:

- The bacterial membrane permeability changes so the antibiotic cannot enter.
- The antibiotic receptor protein on the bacterial surface changes so the antibiotic cannot attach.
- The bacterial metabolism alters and starts pumping the antibiotic out of the cell.
- The bacteria produce enzymes that destroy the antibiotic.

Although antibiotics have been our answer to bacterial invasion since their discovery in 1928, they are not as effective now as they once were. How can this be? Bacteria undergo evolution, just as all life-forms do. Because bacteria have such a short life span, some doubling in as few as 20 minutes, we are able to see evolutionary changes almost immediately. One of those changes has been the introduction and spread of antibiotic resistance genes. These genes allow the bacterium to counteract the effects of a class of antibiotics, and survive despite its introduction. The genes can be passed from one bacterium to the next and even from one bacterial species to the next. Unfortunately, this has meant that medical professionals must always stay one step ahead of the mutating bacterial populations, refining existing antibiotics and discovering new ones.

For a discussion of one type of antibiotic resistance, see *Ethics and Issues: MRSA Causes and Implications*.

We can help prevent the evolution of antibiotic-resistant bacteria by following some simple (and sensible) rules:

- Avoid buying antibacterial soap, as this includes low levels of compounds that stimulate bacterial alterations.
- Take the full allotment of prescription antibiotics, rather than stopping when you feel better. This will ensure that all bacteria are killed, leaving none to develop antibiotic resistance.
- Do not dump old, unused, or expired antibiotics into the water supply.

ETHICS AND ISSUES

MRSA Causes and Implications

WILEY PLUS Video

This is an example of evolution occurring right before our eyes. There is now a strain of staphylococcus bacteria (staph), MRSA, that demonstrates immunity to our most common antibiotics. Genetic changes have occurred within this strain that allow it to survive in the presence of drugs that kill most bacteria. As if that weren't enough of a health risk, there are now two types of MRSA. The first one to evolve was HA-MRSA, or health-care associated MRSA. This strain causes infections in hospitals and nursing homes, where patients are already suffering from weakened immune systems. Recently a second strain has appeared, causing serious skin and soft tissue infections in otherwise healthy people. This strain is referred to as CA-MRSA, or community-associated MRSA.

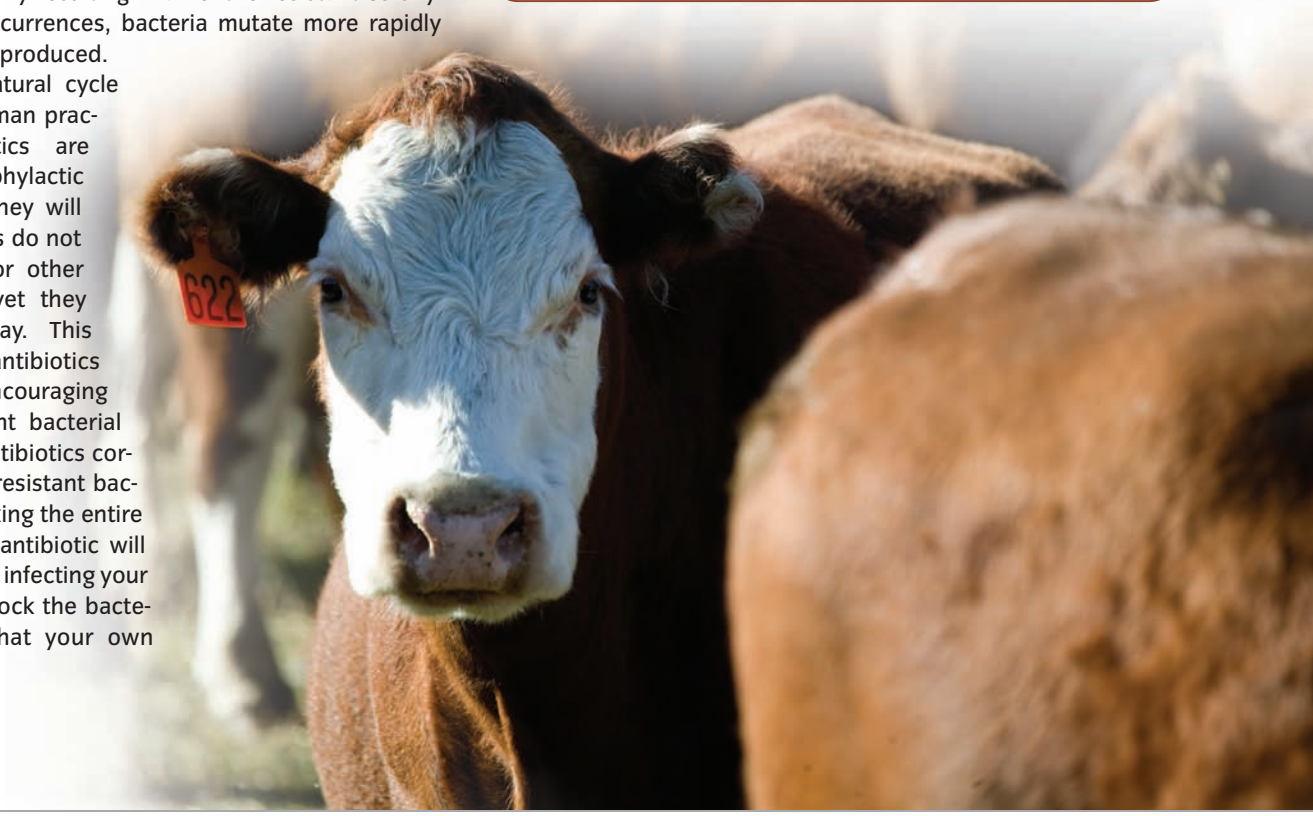
How did this happen? Antibiotics have been in use for disease treatment since the mid-1930s. At that time, sulfanilimides were used to treat infection. Penicillin was released in 1942, and erythromycin appeared in drug stores 10 years later. Since then, doctors have been prescribing antibiotics to control infection. When they are first introduced, new antibiotics are extremely potent. After a few years of use, however, that potency falls. Part of the reason for this is bacteria's natural response to environmental pressures. When the environment of a bacterial colony becomes inhospitable, selection pressures increase. Those bacteria susceptible to the antibiotic fail to reproduce. If even one bacterium is able to escape the lethal effects of the antibiotic, that one cell will reproduce, eventually resulting in an entire resistant colony. Even left to natural occurrences, bacteria mutate more rapidly than new drugs can be produced.

Adding to this natural cycle are some common human practices. Often antibiotics are prescribed as a prophylactic measure even when they will do no good. Antibiotics do not help with colds, flu, or other viral infections, and yet they are prescribed anyway. This leads to an excess of antibiotics in the environment, encouraging the growth of resistant bacterial colonies. Even using antibiotics correctly stimulates drug-resistant bacterial development. Taking the entire prescribed amount of antibiotic will not kill every bacterium infecting your body. It will instead knock the bacterial levels down so that your own defenses can take over. Those bacteria that are left may have survived because they have become resistant to that antibiotic. A final way in which humans increase the chances of developing resistant bacteria is through the use of antibiotics in farming. Most livestock feed includes antibiotics in low doses. These keep feedlot animals healthy and improve their growth rate, both effects increasing profits. Unfortunately, antibiotics can then get into the municipal water, subjecting many bacteria to low levels of antibiotic selection pressure.

Critical Reasoning Issues This is a serious health care problem that is not going to disappear in the near future. In fact, if we do not take positive steps to control the use of antibiotics, MRSA may be only the first of many resistant bacterial threats. Health care as we know it is in jeopardy of returning to that of the Middle Ages in terms of surviving bacterial infections.

Think Critically

1. How can we determine what is an appropriate, yet sparing use of antibiotics? Should this become an economic issue, with antibiotics priced so that only the wealthiest can afford them?
2. Is it feasible to limit the use of antibiotics in farming without jeopardizing the slim profit margin of livestock farming?



NATIONAL GEOGRAPHIC

Several Infectious Diseases Are Bacterial in Origin

Three of the most well known bacterial diseases to reach epidemic proportions are the black plague, leprosy, and tuberculosis. Epidemiologists have made progress in fighting each of these. Recently, however, a strain of bacteria has appeared that is resistant to almost all antibiotics currently known.

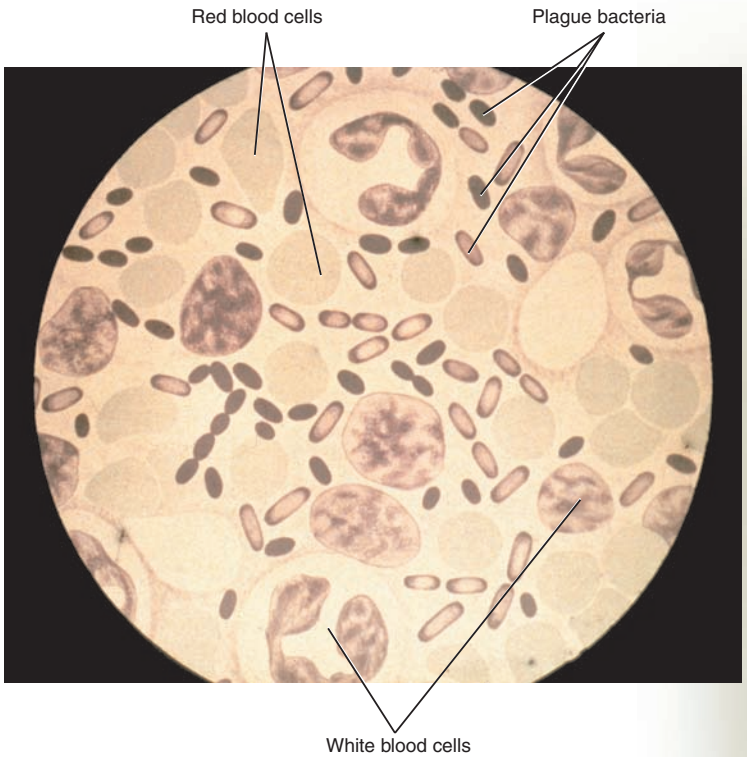
MRSA is resistant to almost all antibiotics. The bacterial strain methicillin-resistant *Staphylococcus aureus* (MRSA) has been in the news a great deal recently. Whereas staph (short for *Staphylococcus aureus*) is a common bacterium on our skin, this particular strain can be a serious, even life-threatening problem if it enters our body in a cut or open wound of any kind, because we cannot treat it. MRSA is resistant to methicillin, amoxicillin, penicillin, oxacillin, and many other common antibiotics. Most staph strains are NOT methicillin resistant.

MRSA appeared in 1961 in isolated hospitals and is now found in many hospitals and emergency rooms. Hopefully, scientists and medical professionals will soon identify a new compound or put together a combination of existing antibiotics that prove effective against this bacterium. As it stands now, an infection with MRSA is a serious condition, currently treatable only with one type of antibiotic: vancomycin. Although vancomycin remains effective against MRSA today, scientists wonder just how long it will take this "super bug" to evolve resistance to our last line of defense.

The black plague is not just an ancient disease. The black plague devastated Europe in the Middle Ages, but it is not merely an ancient disease. The United States suffered a similar black plague epidemic in Los Angeles as recently as 1924–1925. Although not in epidemic proportions, black plague, or bubonic plague as it is now known, still occurs in the southwestern United States, specifically in Arizona, California, Colorado, and New Mexico. Bubonic plague is a serious disease caused by the bacterium *Yersinia pestis*. It is carried in fleas that live on rodents and transmitted with the flea's bite, as shown in **Figure 10.7**. Although humans are not the usual host, they can become infected if bitten by an infected flea. Unsanitary living conditions, coupled with poor hygiene and inadequate medical attention, add to the possibility of contracting plague.

Cause of the black plague • Figure 10.7

The flea shown here is one vector (carrier) of the black plague, or as it is now known, bubonic plague.



A few types of plague differ from one another in the symptoms they cause. Symptoms of the bubonic plague appear two to five days after being bitten by an infected flea. The patient experiences a sudden high fever, rapid weak heartbeat, swollen lymph nodes, and mental confusion, such as restlessness, delirium, and loss of coordination. Most deaths from bubonic plague occur in the early stages of the disease, from day 3 to day 5. **Pneumonic** plague infects the lungs, usually getting there not through a fleabite, but rather via inhalation. Pneumonic plague is highly contagious, as it can be spread through coughing. Symptoms include a sudden high fever, chills, rapid heart rate, severe headache, and coughing. If untreated, it can cause death within 48 hours of symptom appearance. **Septicemic** plague indicates that the bacterium causing the plague is found in the patient's bloodstream. Because the blood travels to every organ of the body, death can result from this form of infection without any symptoms having a chance to appear. In all cases, prompt diagnosis and treatment help to ensure surviving the infection. The antibiotic streptomycin is effective against most strains of plague, and tetracycline is given as a preventative measure should you wish to travel to a plague-prone area.

pneumonic Of or pertaining to the lungs.

septicemic Describes the invasion of a pathogen in the bloodstream; blood poisoning.

Leprosy is not easily contracted. Another epidemic caused by bacteria is leprosy, or Hansen's disease. The bacterium responsible for this disease is a very small organism, even by bacterial standards, called *Mycobacterium leprae*. Discovered in 1873 by G. A. Hansen, this was the first bacterium identified as a human pathogen. Unlike other bacteria, this one multiplies slowly, taking from 5 to 20 years from infection to symptoms. Leprosy is not easily contracted, and it does not spread easily from person to person. Transmission occurs in small droplets from the nose and mouth, but it requires frequent and close contact with the infected individual. Leprosy attacks the skin and nerves, leaving serious scars and dead tissue in its wake. It can be completely cured using a multidrug therapy recommended by WHO. Treatment takes anywhere from 6 to 12 months, and virtually no cases of remission or resistance have been seen using this treatment.

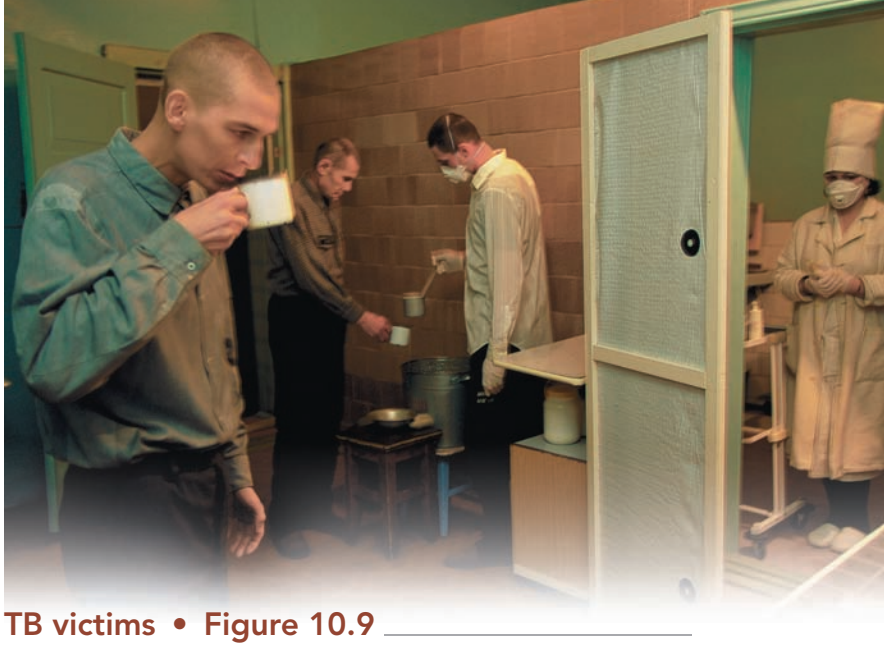
Although one of the first diseases to be described, leprosy remains a health issue today. In 1991, WHO passed a resolution to eliminate leprosy as a public health concern by the year 2000. By elimination of a public health concern, they mean that the disease is reduced to a prevalence rate of less than 1 case per 10,000 people. Not only was this goal reached using the multidrug treatment, but also new cases dropped by an average of 20% per year between 1999 and 2004. In only nine countries does leprosy remain a public health concern, and these nine represent 75% of the global disease burden of leprosy. Most heartening is that over the past ten years, 14 million patients have been cured of leprosy, with 4 million of these cures occurring since 2000. In the previous century, leprosy was seen as a hideous disease, and those who suffered from it were sent away to live in "leper colonies" isolated from the rest of society. **Figure 10.8** was taken at the last active colony in the United States. This town is found on an isolated edge of a small island in the Hawaiian Island chain.

Leper colony • Figure 10.8

Leper colonies, once relatively common, are now rare. However, in 2008 the number of people afflicted with the disease in the United States became a political football, with some claiming that the country had 7,000 new cases of leprosy in the past three years, caused by lax immigration screening. That is not true: The National Hansen's Disease Program records that the United States has had 431 new cases in the past three years.

Tuberculosis usually settles in the lungs. This disease is caused by a bacterium in the same genus as the bacterium that causes leprosy. Tuberculosis, or TB, is caused by *Mycobacterium tuberculosis*. Tuberculosis is transmitted from person to person via droplets from the throat and lungs. It usually settles in the lungs, resulting in respiratory disease. TB can affect other organs too, forming, for example, a tubercular kidney. In many cases, healthy people exposed to tuberculosis will form a nodule of the bacteria in their lungs. The infection will be walled off, and no further symptoms will develop. If however, the patient is suffering from some other respiratory or immune disease, the tuberculosis bacterium can become active. Symptoms of active TB include coughing up blood, weakness, weight loss, chest pains, fever, and night sweats. Given the proper antibiotics, tuberculosis can be treated within six months. **Figure 10.9** shows that TB is still very much with us.

Because people can carry this bacterium without any signs of infection, it is far more prevalent than you might think. According to WHO, someone in the world is newly infected with TB every second. At any given moment, a full one-third of the world's population is infected with TB. Even more frightening, TB is quickly developing resistance to the antibiotics that are used to cure it. Because of this upward trend, in 2006 WHO launched a "Stop TB" strategy. They hope to control the spread of TB by the year 2015.



TB victims • Figure 10.9

TB is a devastating disease. It still is potent: WHO estimates that some 9 million new cases occur in the world each year. These patients are preparing samples to be analyzed for the presence of TB.

CONCEPT CHECK STOP

1. **What** is a prokaryote and **how** does it differ from a eukaryote?
2. **What** is the structure of a typical bacterium?
3. **How** are bacterial infections treated?
4. **What** are five bacterial pathogens?

10.3 Viruses Can Reproduce and Kill, but They Are Not Alive

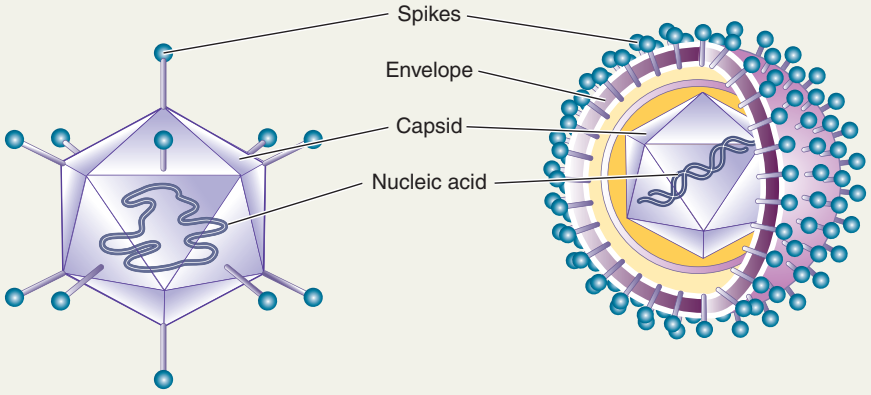
LEARNING OBJECTIVES

1. **Define** the lysogenic and lytic life cycles of viruses.
2. **Describe** why viral epidemics are difficult to control.
3. **List** three viruses that have reached epidemic proportion, and describe the symptoms they cause as well as the way they are transmitted.
4. **Outline** WHO's plans to eradicate polio and measles, and compare this plan to other eradication plans described by WHO.

Viruses are very different from bacteria. Not only are they far smaller, but they also lack most characteristics of life. Viruses cannot reproduce without a **host cell**, they do not metabolize, and they are not composed of cells. A virus is merely a snippet of nucleic acid (either DNA or RNA, but not both) contained inside a protein coat, called a capsid. As scientist Peter Medawar has said, a virus is "a piece of nucleic acid surrounded by bad news." **Figure 10.10** shows these pieces of bad news. Enzymes may be carried within the protein coat

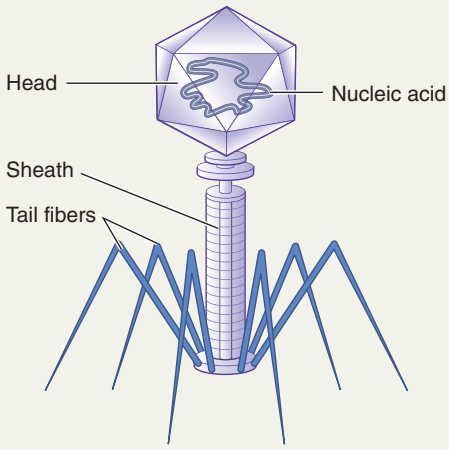
host cell A cell that harbors a virus.

Although viruses cause many different diseases, they have a common anatomy. All viruses exhibit an outer protein coat, or capsid, surrounding nuclear material. The shape of the protein coat can often help identify the virus. For example, Ebola virus always appears in the "tadpole" configuration, while viruses that cause the common cold appear as faceted circles with projections. One of the most striking examples of viral appearance is the bacteriophage, a virus that infects bacteria. Its "lunar lander" shape is the stuff of science fiction!

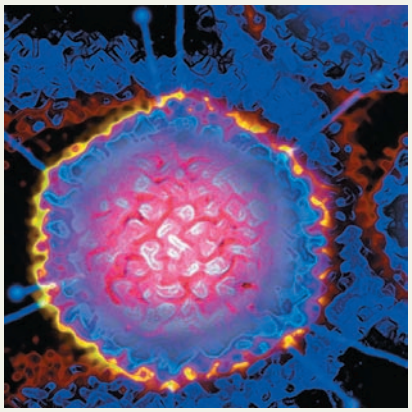


Cold (adenovirus)

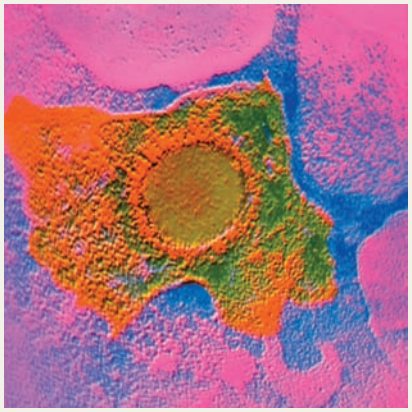
Herpes (herpesvirus)

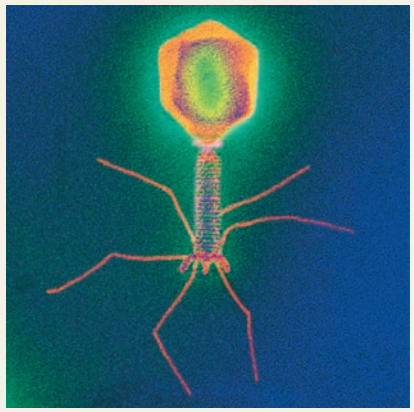


Bacterial virus (T4 phage)

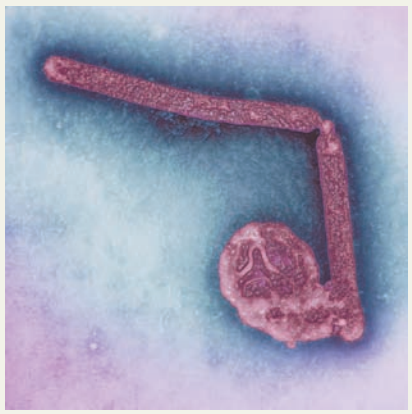


Cytomegalovirus





Ebola virus particle



as well. Ebola, AIDS, smallpox, chickenpox, influenza, shingles, herpes, polio, rabies, and hantavirus are all viral diseases. Some viruses, called bacteriophages, attack bacteria. Because of their small size and ease of purification, bacteriophages are used in research and medicine to introduce genes into cells.

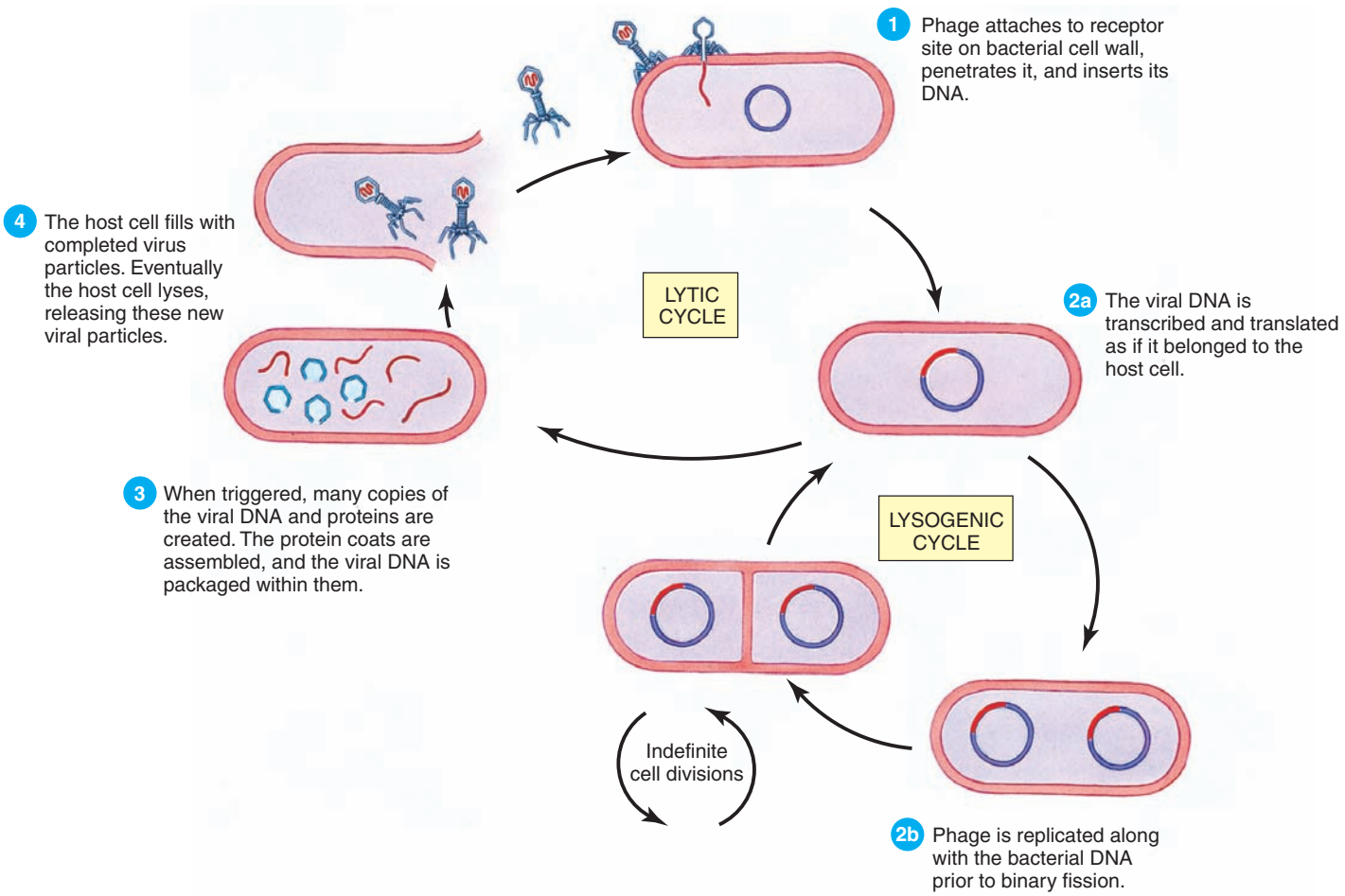
Viruses are cellular parasites. When they contact their preferred host cell, they inject their nucleic acid into the host and take over its functioning. The host cell becomes a viral factory, producing new viruses at an alarming rate.

Viral DNA may remain dormant in the host cell, as happens in viruses that have a "lysogenic cycle" of replication, or it may immediately affect the cell, as occurs in the lytic cycle. Both are depicted in **Figure 10.11**. When viral DNA takes over the host cell, the viral DNA governs the functioning of the host cell. With the proper environmental cue, the dormant virus is stimulated and begins to form new virus particles within the host cell. Eventually, the host cell will fill with virus particles and burst, releasing new viruses into the body. Other viruses, like the adenovirus that is one cause of the common cold, have a lytic life cycle. After infection, there is no dormant phase. Lytic viruses cause the host cell to immediately become a viral factory, pumping out more viruses almost instantaneously.

PROCESS DIAGRAM

Lysogenic and lytic viral phases • Figure 10.11

THE PLANNER



Most Epidemics Are Caused by a Virus

Unfortunately, viruses are not affected by antibiotics. They have no cell wall to break down, no metabolic pathways to destroy, and no protein synthesis to disrupt. This is why you are not given antibiotics when you are suffering from the flu. However, a few drugs can counteract specific viruses. Acyclovir, for example, breaks down into a compound that inhibits replication of the herpes simplex virus. A wide range of compounds are being used to prevent the replication of HIV, the virus that causes AIDS. However, in most cases, when you contract a virus, all that modern medicine can do is treat the symptoms and wait for your immune system to contain and destroy the virally infected cells.

Virus epidemics come in many degrees of severity. What follows is a description of the most common epidemic viruses we face.

Polio attacks the nervous system. *Poliomyelitis* (polio) was a serious threat to infant health just a few short decades ago. Although less prevalent now, polio remains a particularly nasty virus. The virus enters through the mouth, reaches the intestine, and multiplies. From the intestine, polio sometimes attacks the nervous system, rapidly causing symptoms. Incredibly, in the worst cases total paralysis can result after just a few hours of viral attack. Fortunately, for many infected people, polio does not result in paralysis. Just 1 in 100 infected individuals will develop any form of paralysis.

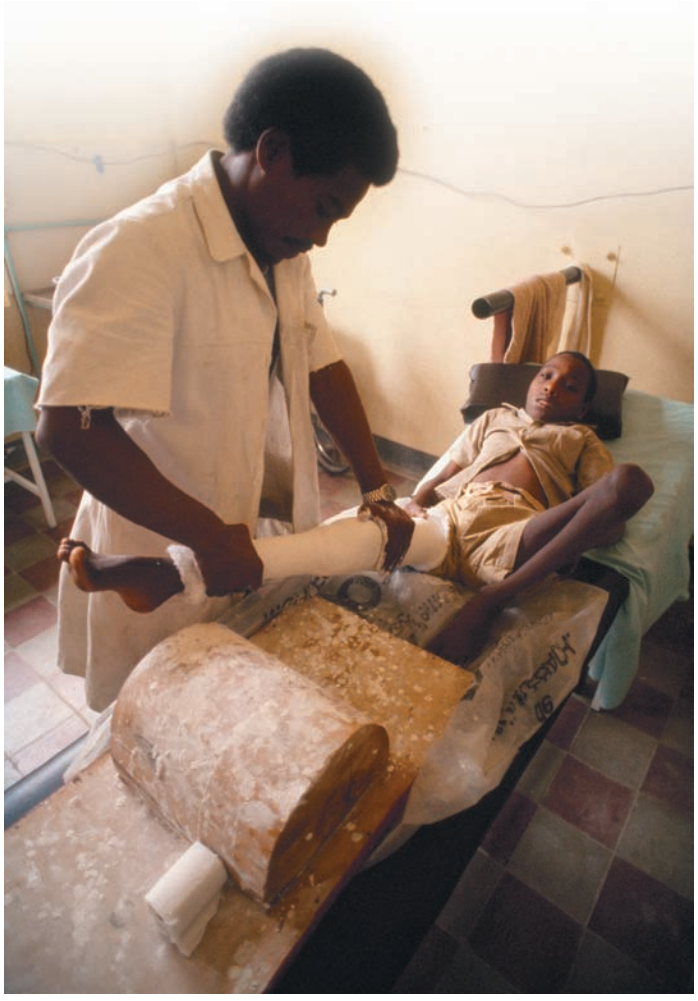
The usual symptoms of the virus are flu-like: neck pain, fever, fatigue, vomiting, and pain in the limbs. Infected people are able to spread the virus for the first few weeks of infection, when they shed newly formed polio virus particles with their feces. Person to person contact also causes the virus to spread, especially in areas where hygienic conditions are poor. Because polio can spread through a population almost silently before any paralysis is seen, it is a difficult virus to track.

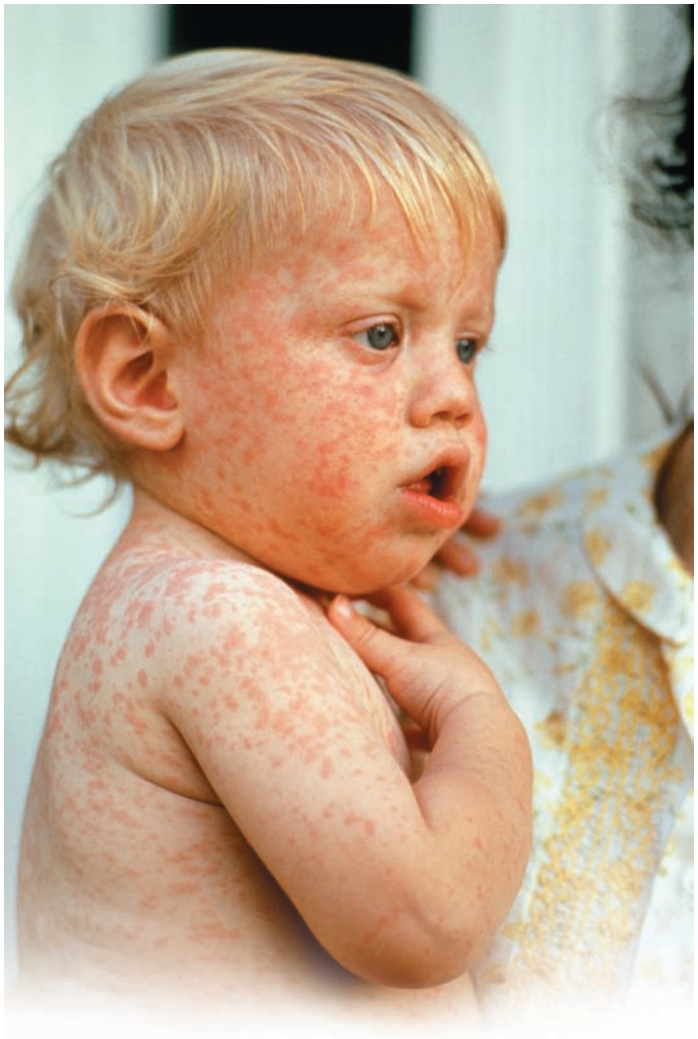
Since 1988, the World Health Organization has worked to eradicate the polio virus from the planet. At the start of this project, the polio virus was found in 125 countries spanning five continents. An average of 1,000 children per day were paralyzed by the virus. With the advent of two polio vaccines, eradication became possible. Involving the resources of national governments, the World Health Organization (WHO), Rotary International, the U.S. Centers for Disease Control and Prevention (CDC), and UNICEF, the Global Polio Eradication Initiative (GPEI) was begun. In 2002, the eradication program was working well, with only three Asian and three African countries reporting cases.

Since then, the vaccination program has been hindered by political instability or armed conflict in some countries and undermined by fear, rumors, and political manipulation in others. For 16 months, for example, religious and political leaders in northern Nigeria refused to allow children in the region to receive the polio vaccine, charging that it was contaminated with HIV and contraceptives. One of the many results of this lapse is shown in **Figure 10.12**. In 2007, a total of 1,314 polio cases were seen worldwide, including 285 in Nigeria and 873 in India. For the first half of 2008, Nigeria saw 353 cases and India 287. Tragically, the polio in Nigeria has spread west to Benin, north to Niger, and east to Chad.

Polio victims • Figure 10.12

A lapse in polio vaccinations allowed 21 countries in Africa to become reinfected with polio in 2003 and 2004.





Measles • Figure 10.13

The typical rash of measles, as seen on this young child, can be overshadowed by even greater health issues, such as measles-induced blindness or life-threatening diarrhea.

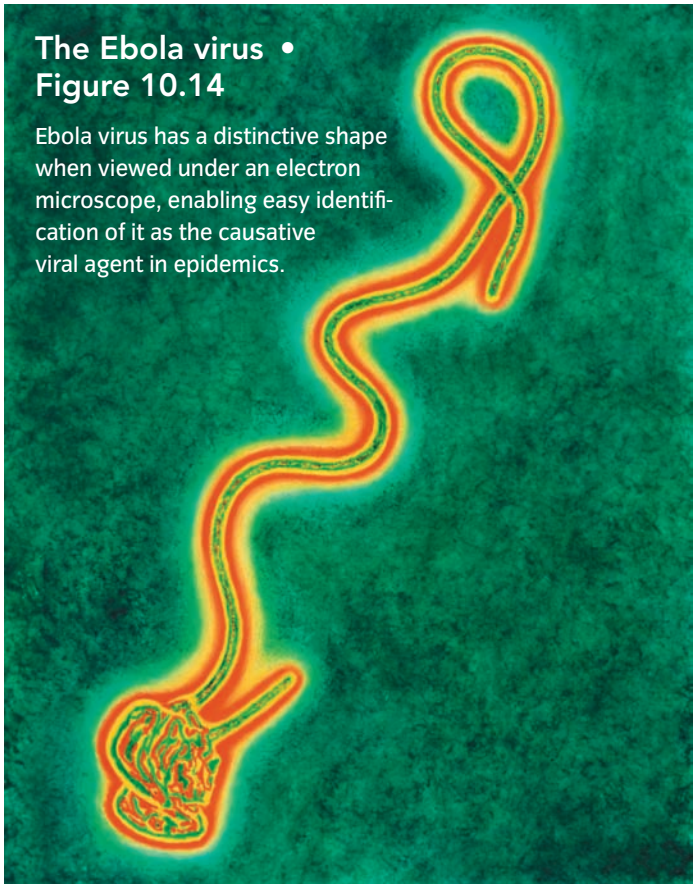
On a brighter note, though, from 1988 to 2008 more than 2 billion children around the world were given the attenuated polio virus vaccine. Because of these efforts, as of 2008 the virus was contained in a very small area of the globe. According to the GPEI, poliomyelitis is currently **endemic** in only four countries: Nigeria, India, Pakistan, and Afghanistan. The GPEI is now working on their post-eradication strategies, employing epidemiologists to determine ways to ensure that the virus does not reappear.

endemic Found only in one area; native to a region rather than introduced.

Measles remains a threat to children. Another deadly virus capable of causing an epidemic is the measles virus. Despite the development of a successful vaccine in 1963, measles remains a serious threat to young children worldwide. Measles is an incredibly contagious disease spread through person-to-person contact as well as through inhaling virally infected droplets released during coughing and sneezing. Once in the body, the virus multiplies in the lining of the throat and lungs. Symptoms of measles begin 10 to 12 days after infection, and include high fever, runny nose, cough, watery eyes, and characteristic white spots inside the mouth. Soon after these white spots show up, the typical measles skin rash develops: small red bumps commonly associated with the disease, as seen in **Figure 10.13**. Although these symptoms are not in and of themselves fatal, children often succumb to complications of the virus. These complications may lead to blindness, encephalitis, severe diarrhea, ear infections, and pneumonia. Pneumonia is the leading cause of death in measles cases.

Although measles eradication is not as well supported as the polio eradication program, UNICEF and WHO are jointly working to reduce the occurrence of measles worldwide. They are targeting 47 countries that comprise more than 95% of the world cases of measles. The strategy for eradication involves four steps: initial vaccination at age 9 months; a second immunization at ages 9 months to 15 years for those not originally immunized; thorough surveillance of areas where the measles virus resides, with prompt case investigations when suspected measles outbreaks occur; and improved clinical management of measles cases that do appear. The goal of this initiative was a reduction in the year 2000 measles mortality by 90% before 2010. This was an attainable but ambitious goal that again depend on epidemiologists and field medical practitioners for implementation.

Ebola is transmitted by direct contact. One of the most frightening viral epidemics of the twenty-first century is Ebola. In 1976, Ebola hemorrhagic fever first caught the attention of the public when entire villages in Sudan were wiped out by the disease. Significant epidemics of Ebola had previously occurred in northern Zaire, southern Sudan, and Yambuka with less publicity than the 1976 event. More recent outbreaks of Ebola have occurred in the Democratic Republic of the Congo in September 2007 and in Yambio, south Sudan, in June 2004. In each case, a team of epidemiologists, virologists, social medicine experts, and infection control professionals were sent to the area to study the



The Ebola virus • Figure 10.14

Ebola virus has a distinctive shape when viewed under an electron microscope, enabling easy identification of it as the causative viral agent in epidemics.

outbreak in the hope of providing clues to its history. Through their efforts, our understanding of this deadly virus is improving. See **Figure 10.14**.

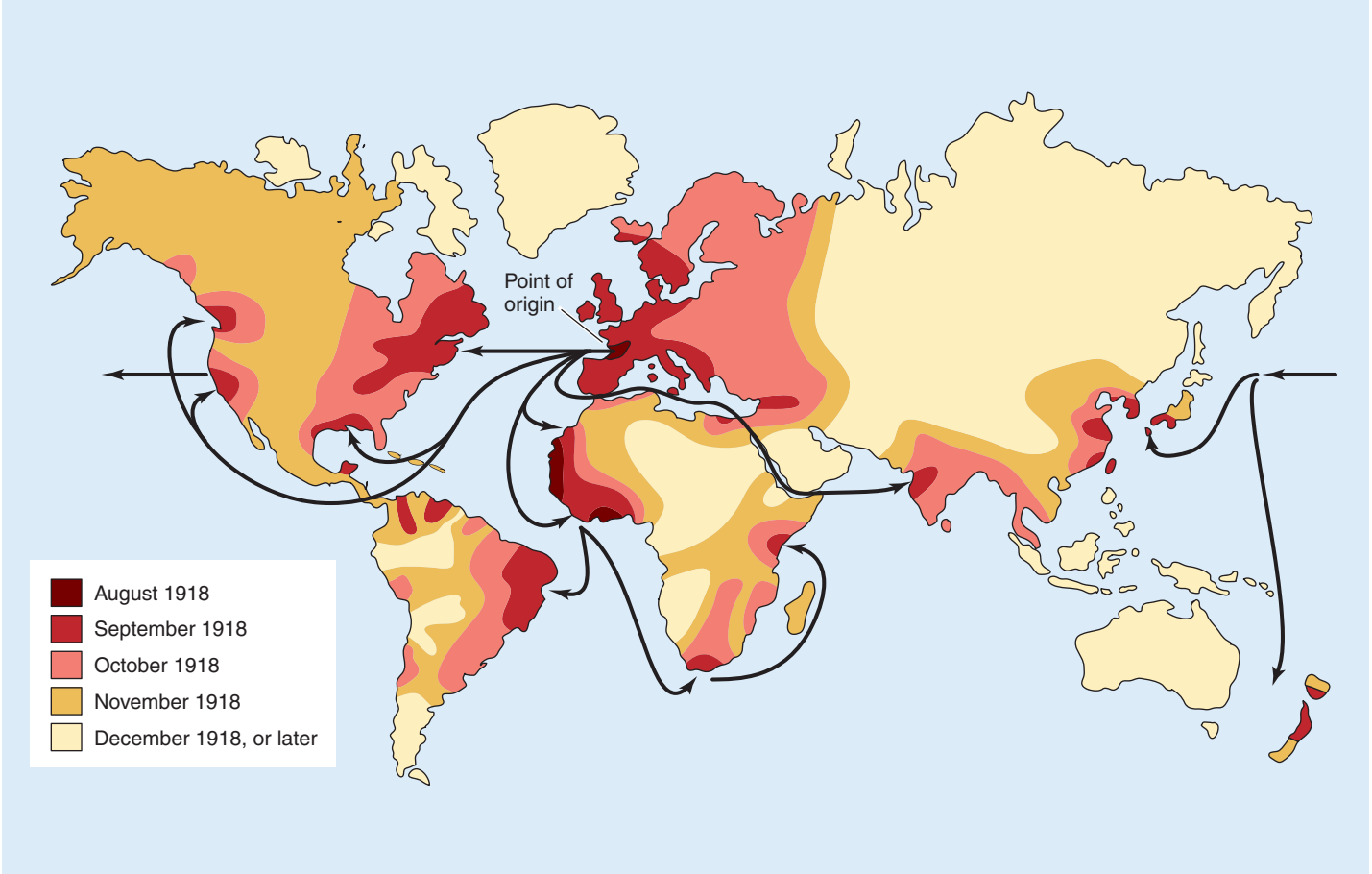
We know that there are four types of Ebola virus in the affected areas, three of which cause human deaths. The reservoir for the virus, or where it resides when not causing an outbreak, seems to lie in the rain forests of the African continent. A less troublesome type of Ebola resides in the western Pacific. The western Pacific virus does not cause any symptoms in humans but does follow the same infection pattern and general biology as the deadly strains. The three strains that do cause symptoms in humans are in fact quite deadly, killing 50 to 90% of those infected. Ebola is transmitted by direct contact with blood and bodily fluids of infected people. Burial ceremonies and cultural grieving practices make it more difficult to contain this disease, as mourners often have direct contact with the deceased. Additionally, there are documented cases of Ebola transfer from chimps and gorillas to humans, and even from patients to their health care workers. Symptoms of the disease begin anywhere from 2 to 21 days after contact. The infected patient will experience sudden fever, intense weakness, severe headaches, muscle pain, and sore throat. As the disease progresses, vomiting, diarrhea, and impaired kidney and liver function appear. Internal and external bleeding is another hallmark of Ebola.

Thus far we do not have an effective vaccine against the disease, nor is there any specific treatment. Unlike measles and HIV, we understand very little about the biology of this virus. Scientists remain uncertain of the original animal host, and they also cannot pinpoint where the virus resides between outbreaks. Some feel that Ebola is a great ape virus, endemic in the chimp and gorilla population. Small mutations in the coat of the virus might allow it to attack humans, causing the outbreaks experienced thus far. Others have hypothesized that the bat is the vector, as research has shown that bats carry the virus but do not succumb to the disease.

The flu virus travels the world. When told what the most devastating epidemic has been to the human population, many people are surprised to hear that the causative agent was the flu. In 1918, the Spanish flu affected large parts of the world, killing in excess of 40 million people. Since then, two different strains of the flu, the Asian flu in 1957 and the Hong Kong flu in 1968, both caused significant numbers of deaths worldwide. Obviously, the flu virus can be extremely dangerous, even though many of us "get the flu" periodically during the winter months, causing us to miss work and activities. The usual flu virus that travels the globe causes respiratory distress, muscle aches, fever, chills, general **lethargy**, and severe headaches. Although uncomfortable, these symptoms do not lead to death in healthy younger adults. In the three pandemics listed above, however, the virus was not the usual strain. Those most affected by the pandemic flu strains were the middle-aged, relatively healthy adults that make up the workforce of developed nations.

lethargy Tiredness and listlessness.

The circulating flu viruses found throughout the world are divided into two subtypes: influenza A and influenza B. Influenza B is the common flu. This virus is easily passed from person to person, traveling through the air in droplets created during coughing and sneezing. One to four days after inhaling viral particles, the viral symptoms are felt. The infected individual can spread the flu virus from a day prior to feeling symptoms to seven days afterward. Because the virus travels in the air, it spreads most effectively in crowded situations. During the winter months, people tend to congregate indoors rather than outside.



Routes of flu transmission • Figure 10.15

The pathway of the 1918 Spanish flu, as it reached pandemic proportions and traveled the globe.

Remaining indoors facilitates the transmission of the flu, as does traveling in commercial airplanes or spending time in any other enclosed, crowded, confined space.

Influenza A is more virulent than influenza B, and is the one responsible for the pandemics of the past century. Its mode of transmission and initial symptoms are the same as those of the common flu. **Figure 10.15** shows the route of transmission of the 1918 Spanish flu. However, the coat of this virus undergoes fairly rapid alterations, making vaccines difficult to prepare. WHO is constantly asking vaccine manufacturers to reformulate the flu vaccine to keep pace with its shifting viral coat. The vaccine includes protection against the three most virulent strains present each year. Because it is difficult to predict just when or where a new influenza A outbreak might occur, flu shots are recommended every flu season. Your doctor may suggest that you or others in your family get such a shot, especially if you fall into a high-risk category. The very young, the elderly, those with compromised immune systems, or even single parents who cannot afford time away from work or family are encouraged to get immunized in case another flu pandemic begins. Often, flu shots are given in a public place, free of charge to those most at risk.

Recently, we have been warned of a potential outbreak of "avian flu" or "bird flu." This is a type A influenza that currently resides in the domestic chicken populations in Asia. This strain has infected humans, causing severe symptoms. Thus far, however, it has not been shown to follow the usual transmission route, instead requiring direct contact with infected foul. The epidemiologists of WHO actively investigate each new case of avian flu to ensure that the virus has not been transmitted via airborne droplets. Should they find that to be the case, we may be facing our next flu pandemic.

Hantavirus is carried by mice. Although not considered an epidemic threat, hantavirus does pose a threat to humans residing in the middle of the United States, in the "Four Corners" area where Arizona, New Mexico, Colorado, and Utah meet. This virus is carried by mice and is spread to humans through inhalation of dust filled with their dried and aerated urine and feces. It has appeared in every state in the west and is spreading to the eastern states as well. The main cause for the spread of hantavirus is the encroachment of humans on the habitat of mice. As we develop the fields they usually call home, the mice move into our houses. Their nor-

mal habit is to urinate and defecate near their nest, resulting in the presence of the mice's urine and associated hantavirus in our homes. Initially, the symptoms of hantavirus are flu-like. Within a few days the patient feels better, and the symptoms abate somewhat. Unfortunately they quickly return, with associated respiratory difficulties. As the virus progresses, the lungs fill with fluid, leading to rapid respiratory failure and possibly death.

West Nile virus is an avian virus. West Nile virus is another viral threat that is increasing as the human population exploits more and more of the world's available habitat. West Nile virus is a bird virus carried by mosquitoes, and when introduced into a human causes inflammation of the brain and tissues surrounding the brain and spinal cord. The virus is an avian virus, transmitted to mosquitoes when they feed on infected birds. If the mosquito then feeds on a human, it transmits the virus to that person. Symptoms of the disease are identical to those of the flu, with body aches, stiff neck, and sore muscles. In some cases the symptoms disappear after 2 to 10 days, while in others neurological damage may be permanent. This disease is spreading through the United States as mosquito populations increase. The CDC is working to combat this disease by researching effective yet less toxic methods of mosquito control.

CONCEPT CHECK STOP

1. **What** is the biggest difference between the lytic and lysogenic life cycles of viruses?
2. **Why** are viral epidemics difficult to control?
3. **What** are three viruses that have reached epidemic proportion? **What** are the symptoms of each and **how** are they transmitted?
4. **What** is the WHO plan to eradicate polio and measles, and **how** does it compare to other eradication plans?

10.4 AIDS and HIV Attack the Immune System

LEARNING OBJECTIVES

1. **Explain** the transmission mode of HIV.
2. **Describe** the infection cycle of a retrovirus.
3. **Describe** the problems that AIDS vaccines have encountered.
4. **Relate** viral pandemics to societal behaviors.

AIDS. We hear bits and pieces about this deadly disease in the news, in health classes, and even at the physician's office. What is AIDS? Why is it so deadly, when many other viral infections can be controlled?

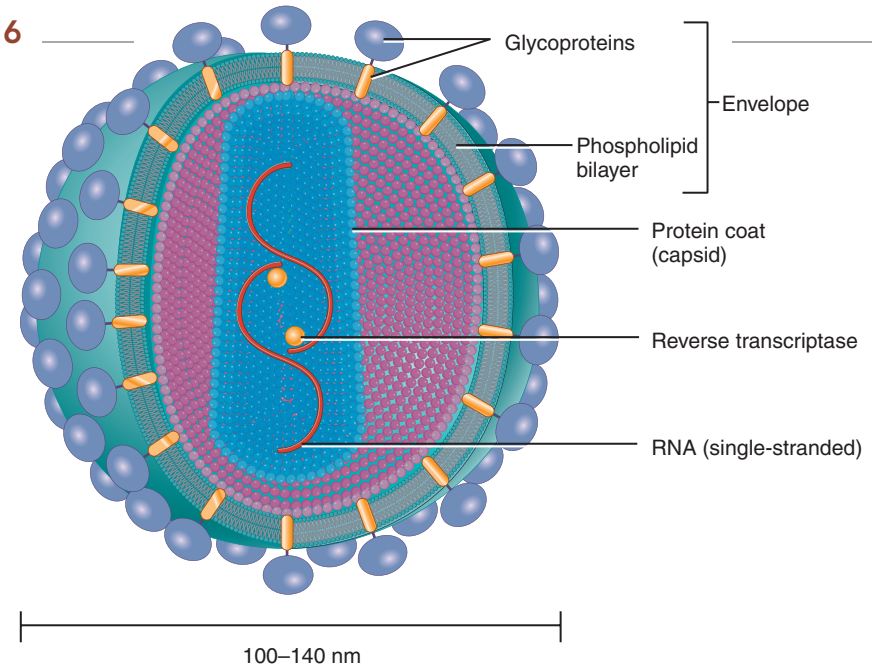
AIDS, from Acquired Immune Deficiency Syndrome, is not actually a viral infection so much as the name for a series of diverse symptoms associated with long-term infection by the Human Immunodeficiency Virus (HIV). These symptoms include extreme loss of weight, cancerous blotches on the skin, **opportunistic infection** with anything that is going around, persistent fevers with accompanying night sweats, chronically swollen lymph nodes, and extreme fatigue not associated with exercise or drug use.

opportunistic infection An infection caused by a common and usually nonthreatening microorganism that is able to cause disease due to a compromised immune system.

To Understand Is to Protect

To avoid contracting AIDS, we must understand the biology of HIV. Unlike many viruses, HIV is unstable outside of body fluids and can survive for only approximately 20 minutes when in contact with drying air and oxygen. This means that most HIV transmission occurs through body fluids. Live viruses can exist in semen, blood, vaginal secretions, saliva, and tears. Thus far, transmission of HIV has been documented only through blood, semen, and vaginal secretions. Even then, transmission often requires an open wound or other tear in the epithelial lining, which gives the viral particles access to the bloodstream.

HIV structure Figure 10.16



Unprotected sex is the primary mode of HIV transmission. Small tears in the vaginal and anal lining that occur during intercourse allow HIV particles present in the semen easy access to the second individual's bloodstream. Sexually transmitted diseases can cause open wounds in these membranes that facilitate the spread of HIV as well. The virus is also prevalent among intravenous drug users who share needles and directly transfer small quantities of blood between bloodstreams. When we understood little about HIV, our blood supply was tainted with the virus, and recipients of blood transfusions occasionally got AIDS. Since the mid-1980s, however, antibody tests have been used to screen out blood contaminated with HIV, essentially eliminating infection through transfusion.

Although the AIDS epidemic in the United States got started among homosexual men, a growing number of heterosexual women carry HIV, and the rate of infection in children under 13 is also rising. The virus can pass across the placenta and through breast milk. According to the CDC, the possibility of an HIV-positive mother giving HIV to her child is thought to be about 25%. However with proper prenatal treatment, including antiretroviral therapy, this number is significantly lower, dropping to 2% or less.

The best way to avoid HIV is to refrain from risky behaviors. Know your partner before engaging in sexual relations, and try to get him or her tested for STDs. Use a condom for protection. Avoid intravenous drug use, and be aware of any accidental blood contact. If you come into contact with another's blood, wash immediately and inspect the skin for cuts or scrapes. Mucous membranes are susceptible because they are penetrable by the very cells that carry HIV. Take extra care not to introduce blood or body fluids to mucous membranes.

HIV Targets the Helper T Cell

The scientific community needs to know more than just the mode of transmission in order to combat the AIDS epidemic. We must also understand what the virus does once it enters the body. We know that HIV targets the helper T cell, also called the CD4 T cell, eventually turning it into a virus factory. We also know the general anatomy of HIV, as shown in **Figure 10.16**.

Because HIV is a lysogenic virus, years can pass between infection and the onset of symptoms. Once HIV enters the body, it travels in the blood, where it eventually contacts a CD4 T cell. The virus attaches to the T cell at the CD4 receptor and fuses with the cell membrane, releasing its components into the host cell.

HIV uses RNA to encode its genetic instructions, so it is classified as a **retrovirus**. In order to infect a human cell, this RNA must be converted to DNA and inserted into the host cell's genetic material. Once inside the host cell, a viral enzyme called reverse transcriptase makes a DNA copy, called cDNA, of the viral RNA. A second viral enzyme then duplicates and inserts this cDNA into the host cell's DNA, so the HIV genetic material becomes part of

retrovirus A virus carrying RNA as its genetic material, along with an enzyme to copy the viral RNA into the host cell's DNA.

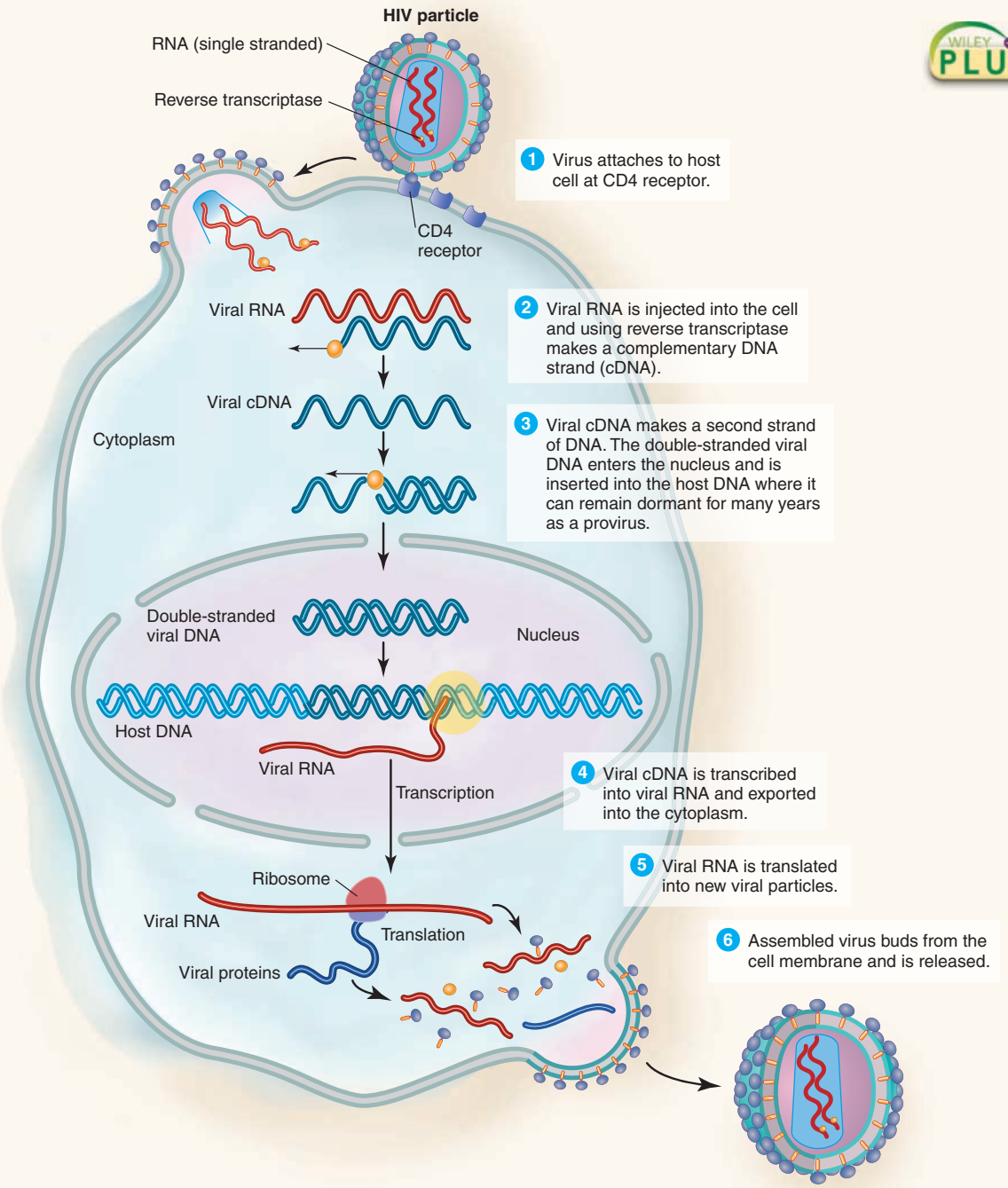
the host DNA. The genes that code for HIV are called a provirus at this point and are indistinguishable from the host cell DNA.

At some point, perhaps 10 to 15 years later, an environmental change occurs in this infected CD4 T cell, and the provirus activates. The provirus then directs the transcription and translation of the HIV genes, shutting off the CD4 T cell's normal functions and turning it into a virus factory. This process is diagrammed in **Figure 10.17**.

PROCESS DIAGRAM

THE PLANNER

HIV reproduction • Figure 10.17



WILEY PLUS Interactivity

The number of viral particles in the blood is called the *viral load*. The viral load is high after the infection, then it drops as the CD4 T cells are infected, which reduces the amount of virus floating freely in the blood. Detection of HIV infection is difficult at this time, as there are no symptoms and the viral load is low. The viral load increases again when the infected T cells start producing more virus.

The infection pattern of HIV causes recognizable stages for patients. During the acute phase of HIV infection, the patient has a high viral load. The CD4 T cell count is normal (500+ per mm^3), and the immune system is functioning normally. A small proportion of people complain of flu-like symptoms during this stage, but the majority of patients have no symptoms because HIV is attacking their T cells.

The number of T cells remains higher than the viral load during this first attack of HIV. Eventually, however, the virus will gain the upper hand. The viral load will exceed the CD4 T cell count, and the patient will suffer chronic infections. This stage can begin a few months to several years after infection. The lymph nodes swell with each infection and remain swollen for prolonged periods, damaging the node tissue. With fewer CD4 cells to initiate the immune response, the patient is susceptible to many diseases that a healthy immune system defeats daily. An AIDS patient is shown in **Figure 10.18**. One indicator disease for this stage of HIV infection is thrush, a yeast infection in the throat and mouth. Uninfected patients easily combat this fungus but not those with lowered T cell counts.

It can take anywhere from 1 to 15 years for HIV infections to develop into AIDS. Once chronic infection sets in, full-blown AIDS—defined as a CD4 count below 200 per mm^3 of blood—is not far behind. The patient suffers a dramatic weight loss, the lymph nodes are damaged beyond their ability to function, and opportunistic infections like *Pneumocystis carinii* pneumonia, tuberculosis, or Kaposi's sarcoma attack the body. The patient usually succumbs to one of these infections, so death is an indirect result of the HIV infection.

AIDS patient • Figure 10.18

In a full-blown AIDS patient, the immune system is usually overwhelmed, and chronic opportunistic infections set in. The patient must treat all these opportunistic infections, as well as the HIV virus itself. This results in an overwhelming number of prescription drugs for the patient.

HIV Treatment Remains an Uphill Battle, and Vaccines Are Hard to Make

Although AIDS cannot be cured, we are getting better at controlling the virus and its symptoms. The current state-of-the-art treatment is called highly active antiretroviral therapy (HAART), which includes nucleotide analogs and protease inhibitors. Protease inhibitors block the enzyme protease needed to produce new viral particles. Nucleotide analogs, like AZT, are structurally similar to one of the four DNA nucleotides, and they prevent creation of the HIV proviruses in infected cells. The analogs are picked up during transcription and added to the growing mRNA molecule. The analogs stop the formation of the new chain by inhibiting reverse transcriptase from completing the chain. These treatments are effective but demanding. The patient must take a complicated regime of pills throughout the day, and the side effects of these medications commonly include diarrhea, hepatitis, and diabetes.

HIV mutates too quickly for vaccinations to work. Many viral pathogens, including smallpox, polio, and chickenpox, are controlled by vaccines, so it is logical to think a vaccine would control the AIDS epidemic as well. Medical experts are working on a preventative vaccine for those not yet infected with the virus and on a therapeutic vaccine for those already infected, but HIV vaccines do not yet work. Traditional vaccines use an attenuated viral particle, with an intact protein coat but no capability of causing infection. Injecting attenuated virus into a healthy person triggers the production of antibodies toward the viral coat.

Unfortunately, HIV mutates too quickly for this tactic to work. Even if a vaccine did work against one strain of the virus, the virus changes so quickly that the vaccine

HEALTH, WELLNESS, AND DISEASE

WILEY PLUS Video

Current Actions in Worldwide Disease Prevention

Sometimes the smallest actions have the greatest impact. HIV is an ongoing health concern in Africa, and often seems overwhelming in scope. Volunteers, scientists, and medical professionals have been working to stem the flow of this virus for many years. Recently a program using simple technology is making a visible difference in public awareness.

Project Masiluleke is the signature program of PopTech Accelerator. This group designs novel solutions to global challenges. Masiluleke, the Zulu word for "hope," began when an HIV+ South African woman, Zinhle Thabeths, came to PopTech to speak about the devastating effects of HIV on her family, community, and country. After her presentation, PopTech began working on increasing public awareness of HIV testing and social services in South Africa. When they discovered that nearly every South African has access to a mobile phone, a remarkably easy plan took shape. "Please Call Me" (PCM) is a free text-messaging system used in South Africa. Combining this text-messaging space with technologies and content donated by Praekelt foundation, iTeach, frog design, and MTN, a public service message will soon be broadcast to millions of South African mobile phone users. The message will provide the AIDS helpline number, and a number to call for information on TB and HIV testing. Messages are to be sent at a rate of 1 million per day, every day for an entire year. Initial testing of this service has already tripled the average daily call volume to the National AIDS Helpline in Johannesburg.

would be useless in a very short time. Those vaccinated against the original strain could succumb to the newly mutated one. Scientists are looking into vaccines that stimulate the immune system using an integral part of the viral coat, such as the portion that initiates contact with the T cell. Thus far, several dozen vaccines have been tested in the United States or overseas. In July 2005, two vaccines reached phase-three trials, the last hurdle before licensing, but neither one worked well enough to proceed. At present, the only good advice regarding HIV is this: the disease is fairly easy to prevent and impossible to cure. Prevention matters, and it works. See *Health, Wellness, and Disease: Current Actions in Worldwide Disease Prevention* for more on what we are doing about this disease and others.

Pandemics May Force a Change in Familiar Social and Economic Arrangements

When a new virus breaks out, neither vaccine nor cure is likely to be available. International scientific and public health cooperation is needed to combat diseases that often originate and survive in regions where the necessary scientific, social, and financial resources are in short supply. Epidemics can cause fear, resentment, and rumor. Some conspiracy theorists have blamed AIDS on plots by spy agencies or on failed vaccination campaigns. The government of South Africa, with perhaps the worst infection rate in the world, has refused to admit that HIV causes AIDS. This antiscientific attitude makes prevention campaigns nearly impossible.

The first step in confronting an epidemic is to understand the science of the pathogen. However, scientific knowledge becomes useful only when we use it to identify the economic and social practices that spread the disease and then act to change those practices. The AIDS pandemic has shone a light on social customs that spread deadly pathogens. Unsafe sexual practices and the unsanitary use of IV needles are partly responsible for transmitting HIV in various places.

In many countries, more women than men are infected. Even if these women know how to protect themselves against infection, many lack the social power to enforce monogamy or condom use. Thus, educating and empowering

women becomes a key strategy in slowing a pandemic that is undoing decades of hard-won economic progress in poor countries.

Pandemics may force a change in familiar economic arrangements. At some point, does the reality that poor countries need access to life-saving medicines overcome the patent rights of drug companies? Much of the recent progress against AIDS has come from broader use of antiviral medicines. India, for example, chose to bend patent laws to slow the AIDS epidemic by manufacturing generic versions of patented medicines. For too many years after expensive antivirals had begun saving lives in rich countries, AIDS remained a death sentence in poor countries. However, the United Nations says that is changing: "More than one million people in low- and middle-income countries are now living longer and better lives because they are on antiretroviral treatment." These drugs saved an estimated 300,000 to 400,000 lives in 2007.

In retrospect, many governments bungled the initial response to AIDS by denial or by staging lame, uncoordinated campaigns against infection. To date, no HIV vaccines work. Even though we have relied on vaccines to control viruses for a century, for the foreseeable future the battle against AIDS will focus on changing behavior and maximizing the use of imperfect medicines.

CONCEPT CHECK STOP

1. **How** is HIV transmitted?
2. **How** does a retrovirus replicate inside the host cell?
3. **Why** is there currently no vaccine for HIV?
4. **How** do viral pandemics relate to societal behaviors?

10.5 Other Pathogens Carry Other Dangers

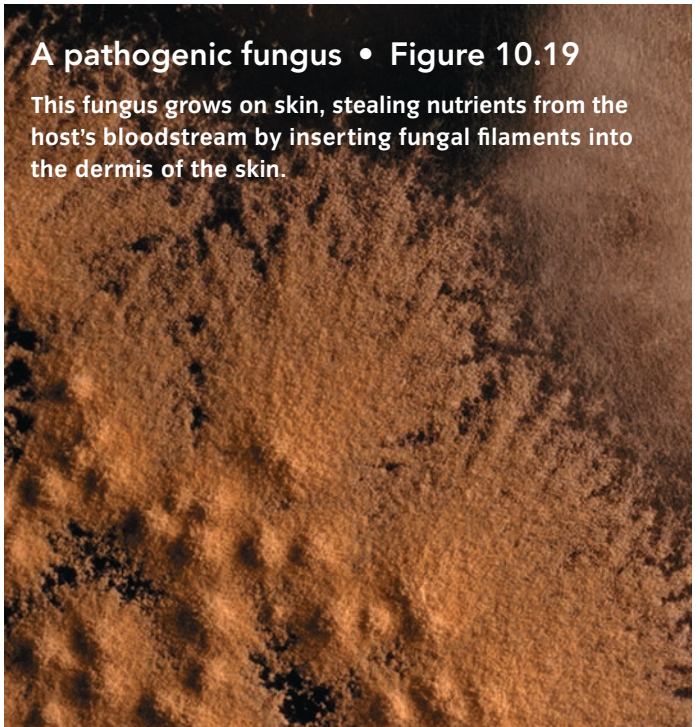
LEARNING OBJECTIVES

1. **List** three categories of pathogens other than viruses and bacteria.
2. **Explain** the functioning of a prion, the causative agent of mad cow disease.

Three other categories of pathogens other than bacteria and viruses can attack human beings in the proper conditions: fungi, protists, and prions. Each of these has its own way of making us sick.

Fungi Are Eukaryotic Organisms that Play a Major Role in Decay Processes

The fungi that you are most familiar with include mushrooms and molds. Fungal diseases in general are more common in warm, moist conditions. They can range from athlete's foot, a skin infection, to yeast infections of the female reproductive tract. Aspergillosis is a fungal infection of the respiratory tract that can cause asthmatic symptoms. Zygomycosis is a fungal infection of the blood vessels that is predominantly found in patients with a compromised immune system due to an underlying disease. Fungi generally do not cause epidemics, perhaps due to the nature of their growth and their mode of infection. A pathogenic fungus is shown in **Figure 10.19**.



A pathogenic fungus • Figure 10.19

This fungus grows on skin, stealing nutrients from the host's bloodstream by inserting fungal filaments into the dermis of the skin.

Amoebic dysentery cause • Figure 10.20

Amoebic dysentery is caused by protists just like this one.

Protists Include Unicellular Organisms

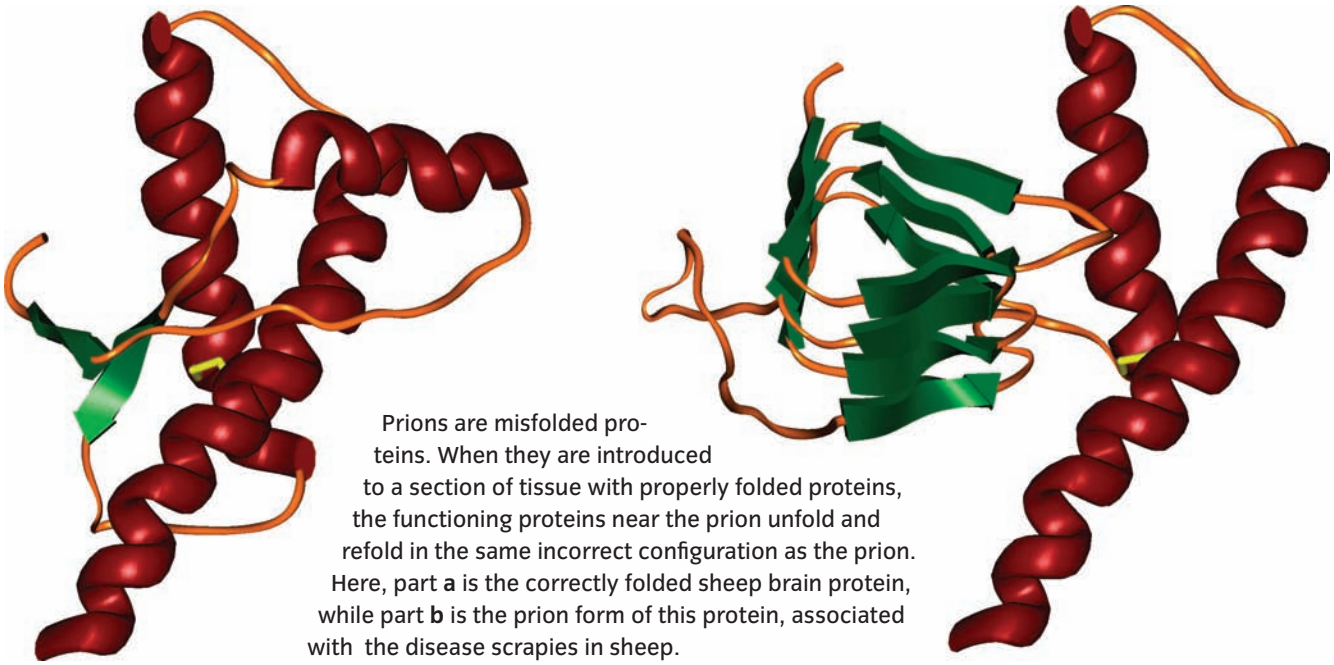
Amoeba and paramecium are protists. Both of these simple creatures can survive within the human body. Amoeba are contracted from contaminated water sources and are responsible for **dysentery** in many parts of the world. Amoebic dysentery can reach epidemic proportions in areas with poor sanitation. Another amoeba has recently been isolated from freshwater lakes in the eastern United States. Although this amoeba is rare and unlikely to reach epidemic status, contraction of it is deadly as it resides in and destroys the brain tissue of its host. Learn more about this amoeba in *I Wonder… An Amoeba that Eats Human Brains?* in Chapter 7. **Figure 10.20** depicts the culprit in amoebic dysentery.

dysentery Severe diarrhea accompanying swelling and bleeding of the lower bowels.

Protists are responsible for a wide-ranging group of diseases, including malaria and leishmaniasis. Malaria is a serious disease worldwide, infecting approximately 515 million people per year, and killing 3 to 4 million. It is most common in areas where the carrier, the *Anopheles* mosquito, can be found. Malaria is caused by a protist, *Plasmodium* sp., carried in the salivary glands of the *Anopheles* mosquito. When a person is bitten by a carrier mosquito, the immature protists are injected into the human bloodstream. The *Plasmodium* larvae migrate to the red blood cells, where they burrow in and complete their life cycle, multiplying until the red blood cells burst, releasing new *Plasmodium* protists to continue the infection cycle within the host. Symptoms of malaria include anemia as the red blood cells are lost, fever, chills, nausea, and flu-like symptoms. In severe cases, death may result as many red blood cells are lost. Currently, there is no vaccine against malaria, but some success is seen in treating the disease with quinine and quinine derivatives. Mosquito control is the best prevention for the spread of malaria.

Leishmaniasis is another common disease caused by a protist. In this case, the protist is transmitted by the bite of a sandfly found in forests, caves, and rodent burrows. This protist causes lesions on the skin or mucous membranes. In the least severe form of leishmaniasis, skin ulcers appear

Prion activity • Figure 10.21



Prions are misfolded proteins. When they are introduced to a section of tissue with properly folded proteins, the functioning proteins near the prion unfold and refold in the same incorrect configuration as the prion. Here, part **a** is the correctly folded sheep brain protein, while part **b** is the prion form of this protein, associated with the disease scrapies in sheep.

a. **b.**

that will heal and scar within a few months. More severe forms of this disease include diffuse cutaneous leishmaniasis, in which the skin lesions appear over the entire body rather than just at the bite area, and mucocutaneous leishmaniasis, causing ulcerations in mucous membranes of the nose, mouth, and throat. These ulcers eventually destroy the mucous membranes in which they are found. A final form of this protist infection is visceral leishmaniasis. In this form, the individual suffers high fever, extreme weight loss, and swelling of internal organs, such as the spleen and liver. If no treatment is provided, visceral leishmaniasis will lead to death within two years.

Prions Are Misshapen Proteins

Prions have even fewer of the characteristics of life than viruses, as they are merely a protein with an odd conformation. In other words, the primary structure of the protein is correct, but something happens that causes the secondary and tertiary structures to fold inaccurately. A schematic of this is shown in **Figure 10.21**. We are unsure of the mechanism by which this happens, but when prions enter a healthy brain, they cause similar healthy proteins to unfold and refold incorrectly, resulting in a chain reaction of destruction. Prions can attack the brain proteins in a wide range of mammals, from deer to cats to humans. These diseases are untreatable and fatal but extremely rare.

When epidemiologists found in the 1990s that all patients with a disease called Creutzfeldt–Jacob disease, a deadly disorder affecting the human nervous system, had eaten meat from cows probably infected with bovine spongiform encephalopathy (BSE, better known as "mad cow disease"), they suspected and feared a connection between the two. Many epidemiologists now believe that prions are the cause of both diseases.

CONCEPT CHECK STOP

1. **What** are three categories of pathogens other than viruses and bacteria?
2. **How** do prions function?

Summary

THE PLANNER

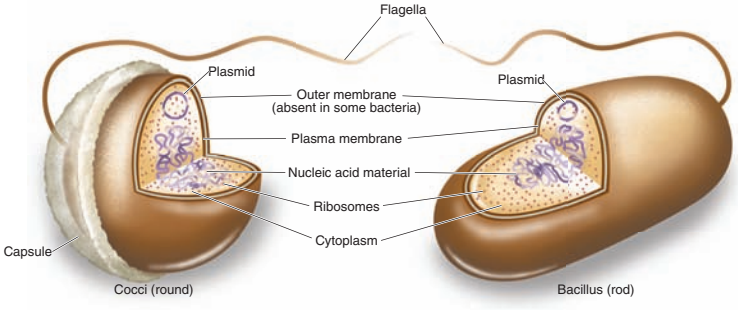
1 The Study of Epidemics Is Global in Scope 246

- Epidemics are diseases that affect many people at once, spreading rapidly via infection from one person to the next. If the disease affects a large portion of the globe, it is referred to as a pandemic.
- Epidemiologists study the symptoms and the spread of epidemics through case studies, case control studies, **cohort** studies, and outbreak investigations. Case studies are exhaustive, complete individual patient histories. Case control studies seek to understand the method of infection of the epidemic. **Cohort** studies help identify those individuals most at risk during the epidemic, and outbreak investigations are carried out by trained scientists and medical professionals at the scene of the appearance of an infectious disease.
- Since 1948, the World Health Organization has been responsible for monitoring and predicting pandemics for helping national health organizations coordinate healthcare worldwide. This organization studies new outbreaks, directs the research on the flu virus, and initiates global eradication schemes for some of the most difficult epidemics. Epidemics have been caused by viruses and bacteria, although some scientists are now worried that prions may also cause an epidemic in the years to come.

2 Bacteria Are Single-Celled Wonders that Can Cause Disease 251

- Bacteria are **prokaryotic** cells. As shown, they have a cell wall, a cell membrane, ribosomes, a circular piece of DNA anchored to the cell wall, and some intracellular fluid. Bacteria are classified by shape, Gram staining, and genetics. Antibiotics kill bacteria by disrupting their cell membranes or other metabolic processes.

Figure 10.6



- MRSA is an antibiotic-resistant strain of *Staphylococcus* bacteria causing problems for patients since 1961.
- Three of the most well-known bacterial diseases to reach epidemic proportions are the black plague, leprosy, and tuberculosis. The black plague (also called bubonic plague) is a bacterium carried by rats and mice. It is transmitted to humans through fleabites and causes sudden high fever, rapid weak heartbeat, swollen lymph nodes, and mental confusion, such as restlessness, delirium, and loss of coordination. Most deaths from bubonic plague occur in the early stages of the disease, from day 3 to day 5. Leprosy is caused by a slow-growing bacterium that can take up to 20 years to cause symptoms, and it is difficult to spread. It attacks the skin and nerves. Recently a treatment for leprosy has been identified. Nevertheless, leprosy remains a global health concern. TB is also a serious health concern. Carried in droplets suspended in the air, it is easily spread from person to person. TB can remain in one area of the body, or it can spread throughout the body. According to WHO, someone in the world is newly infected with TB every second.

3 Viruses Can Reproduce and Kill, but They Are Not Alive 258

- Viruses are small bits of nucleic acid covered in a protein coat, but they are not considered alive. Antibiotics have no effect on viruses, leaving us with little recourse other than to treat the symptoms of the virus and wait as it runs its course through the body.
- Viruses can exhibit either a lytic or a lysogenic life cycle. Lytic viruses infect a cell and immediately convert that cell to a viral factory. Lysogenic viruses remain dormant in an infected cell for days to years before converting that cell to a viral factory and causing disease.
- Most of our epidemics have been viral in origin. Despite the aggressive efforts of WHO, polio remains a health issue. A vaccine has been developed, and with vigilant administration shows promise of eradicating polio from the globe. Measles is also caused by a viral infection, and both UNICEF and WHO are working to eradicate this virus. Ebola, pictured here, is a relatively recently discovered virus and is threatening to reach epidemic proportions in Africa. No vaccine exists for Ebola, nor do scientists understand much about its life history. The influenza virus has been responsible for the worst pandemic in recorded history, the Spanish flu of 1918. Influenza A is a virulent form of the virus, mutating and causing epidemics, whereas influenza B remains fairly innocuous.

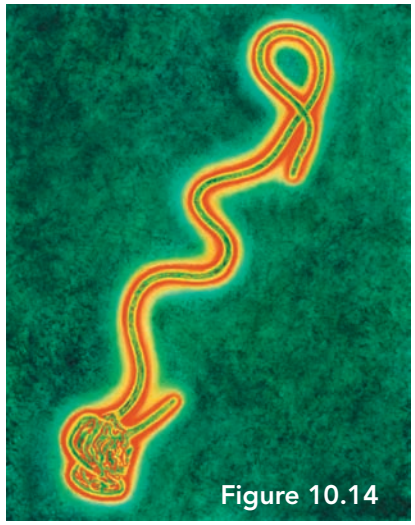
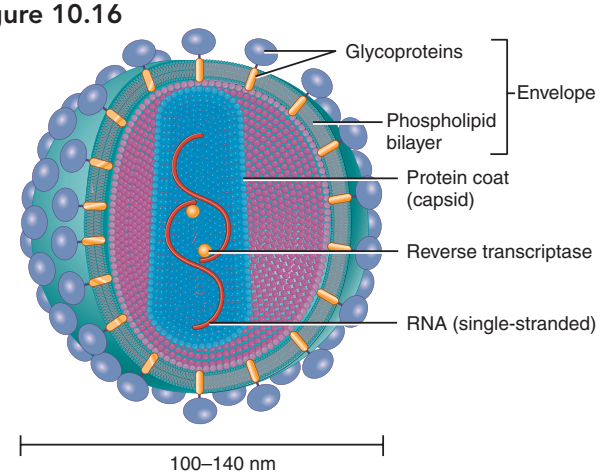


Figure 10.14

4 AIDS and HIV Attack the Immune System 265

- HIV is a blood-borne viral pathogen that leads to death via AIDS. It is a retrovirus, infecting individuals through blood-to-blood contact that usually occurs during unprotected sex or use of contaminated needles. The cycle of HIV begins with introduction of the virus, shown here, into the bloodstream. It then attaches to and invades a host CD4 T cell, where it copies its own RNA into cDNA. Next, the viral genes are inserted into the host cell DNA. Symptoms are negligible at this point. Years later, the infected CD4 T cells begin to produce virus, increasing the viral load of the patient and decreasing the T cell count.

Figure 10.16



- AIDS is diagnosed when the CD4 T cell count drops below 200 per mm^3 and the patient is suffering from opportunistic infections that healthy individuals' immune systems easily fight off. Vaccine treatment for HIV remains out of reach, but researchers are getting closer to success.

5 Other Pathogens Carry Other Dangers 270

- Fungi, protozoans, and even misshapen proteins can also cause disease. The most common fungal infections are athlete's foot, thrush, and yeast infections of the female reproductive tract. These diseases do not generally cause epidemics. Protists, such as the amoeba, can cause serious health concerns, and amoebic **dysentery** can reach epidemic proportions in countries with poor sanitary practices. Malaria and leishmaniasis are examples of disease caused by protists carried in the bite of an insect. Malaria is a constant threat in tropical climates, reaching epidemic proportions annually.
- Prions are misshapen proteins that affect normal proteins in the brain. If introduced to healthy brain tissue, prions may cause healthy brain proteins to malfunction. Mad cow disease is caused by prions.

Key Terms

- cohort 246
- dysentery 271
- endemic 262
- host cell 258
- lethargy 263
- opportunistic infection 265
- paradigm 246
- photosynthesis 251
- pneumonic 257
- prokaryotic 251
- retrovirus 266
- septicemic 257
- socioeconomic level 247

Critical and Creative Thinking Questions

1. Dengue fever is a tropical disease that, by 2005, had reached epidemic proportions in Malaysia and Vietnam. The disease spreads quickly by the *Aedes aegypti* mosquito. Explain how a vaccine might slow this epidemic. What characteristics would the vaccine need? What are the differences between the primary and secondary immune responses in terms of a dengue vaccine?
2. *Herpes simplex* (*HS*) is the name for a group of viruses that attack human cells. This virus is lysogenic, causing cold sores (HSI) or genital warts (HSII). Both of these varieties display as open canker sores that periodically reappear. Review the lysogenic cycle of viral infection and then describe what is happening within an infected cell during the appearance of a cold sore.
3. The flu is a serious problem for WHO. Why is this so? It seems like a minor inconvenience, leaving most of us ill for a mere few days. Why is influenza still a number one priority of WHO? What can you say about the origin of a serious influenza epidemic?
4. Assume that you are an epidemiologist living in Arizona. You notice that many of your associates in your small town are exhibiting symptoms of hantavirus. Describe the steps that you would take to, first, determine whether there is in fact an epidemic in the making in your town and, second, help control the spread of the virus.

5. **CLINICAL CLICK QUESTION**

Julian felt fine just a few hours ago, but now he was chilled, and overly tired and his head was pounding with a terrible headache. When he took his temperature, it was over 100 degrees. After a nap, Julian's symptoms had worsened, including a severe sore throat and an increase in temperature. Although he rested and stayed in bed for the rest of the day, Julian's symptoms continued and his fever slowly crept upward. Julian reflected on where he might have picked up this disease. He had attended his college football game five days ago, and had picked up his visiting relatives at the airport just two days ago. After three days Julian felt no better, so he went to the doctor. As he described his symptoms, the doctor told him that there was not much he could do to get rid of Julian's illness, but he could treat the symptoms. Julian was given some medications to help alleviate the fever and reduce the pain of his sore throat. A history of Julian's activities over the past two weeks was recorded for the state reporting agency, as Julian was diagnosed with a disease that was being closely monitored by the CDC. What type of illness might Julian have contracted that would cause symptoms so quickly? Is it possible that he contracted this disease at the football game or at the airport as he thought? What key symptoms led the doctor to recognize Julian's illness? Why did the CDC need to be notified of Julian's illness? To verify your diagnosis, visit http://www.cdc.gov/swineflu/swineflu_you.htm

What is happening in this picture?

Scientists dressed like this occur only in Hollywood movies, right? Wrong! These epidemiologists are at the outbreak site of an epidemic, studying exactly what happened. They will take tissue samples from infected individuals and also samples of the environment to assist in determining where the disease rests between epidemics.

Think Critically

1. Specifically what natural disease-prevention systems do these seemingly overdone suits reinforce?
2. What do you suppose might be the causative agent these epidemiologists are trying to protect themselves from?
3. Other than tissue and blood samples, what types of samples might these scientists remove from the infection area?

Self-Test

1. A pandemic differs from an epidemic in that _____.
   a. a pandemic causes disease in one group of people only
   b. epidemics are worldwide, whereas pandemics are local
   c. pandemics are worldwide, whereas epidemics are local
   d. WHO involves itself only in epidemics

2. Epidemiologists use cohort studies to _____.
   a. form hypotheses about the cause or treatment of a disease
   b. shed light on the method of infection of a disease
   c. estimate the likelihood of infection among certain groups of individuals
   d. verify the diagnosis of the disease, define the symptoms, and collect data

3. Clinics in impoverished rural settings, like the one in this photo, are often set up and run by _____.
   a. the CDC
   b. WHO
   c. local philanthropic medical practitioners
   d. the Red Cross

4. The only viral disease ever successfully eradicated from the globe through a WHO initiative is _____.
   a. smallpox
   b. polio
   c. German measles
   d. HIV

5. The type of bacteria found in long chains of spherical organisms is _____.
   a. staphylococcus
   b. coccus
   c. bacillus
   d. streptococcus

6. Bacteria are prokaryotes, meaning that _____.
   a. they have ribosomes
   b. their internal organization is similar to that of our own cells
   c. their DNA is stored within a membrane-bound nucleus
   d. they have only the cell membrane to carry out complex processes

7. MRSA is particularly challenging to medical professionals because _____.
   a. it is derived from a common bacterium normally found on our skin
   b. it shows resistance to many of the common antibiotics in use today
   c. it is found in many hospitals and emergency rooms
   d. All of the above are true of MRSA.

8. The organism shown here is the vector for _____.
   a. the black plague
   b. leprosy
   c. TB
   d. the West Nile virus

9. Which of the following bacterial pathogens has WHO recently launched a program to eradicate?
   a. leprosy
   b. septicemic plague
   c. tuberculosis
   d. pneumonic plague

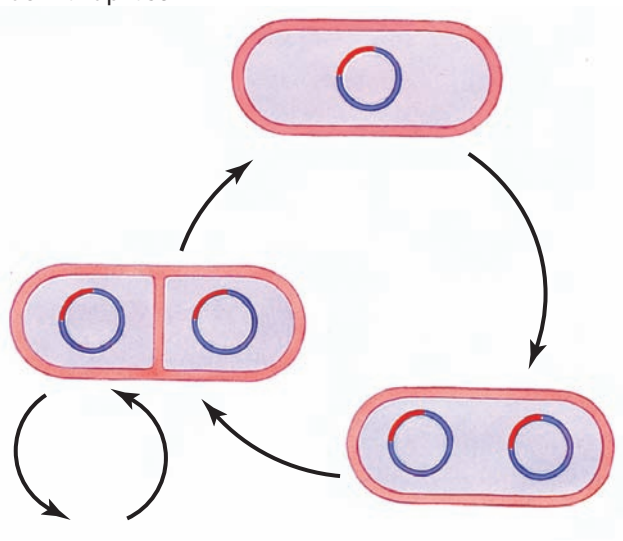
10. The phase of the viral life cycle depicted below is the _____.

a. lytic phase

b. lysogenic phase

c. replication phase

d. dormant phase



11. Viruses are controlled using antibiotics.

a. True

b. False

12. Polio is a virus that _____.

a. is now endemic to only four countries

b. has spread from Nigeria to other countries

c. was found in 125 countries but has been reduced by a collaborative and global initiative

d. All of the above options are correct.

13. The flu vaccine is constantly reviewed and reformulated because _____.

a. WHO has no idea which flu strain will cause the next epidemic

b. influenza B viruses are hard to isolate in the lab

c. the avian flu may some day mutate to an airborne form

d. influenza A viruses mutate quickly, necessitating new vaccines

14. HIV attaches to the CD4 protein coat complex of the _____, obtaining entry to the cell, where it may lie dormant for many years.

a. cytotoxic T cell

b. helper T cell

c. B cell

d. macrophage

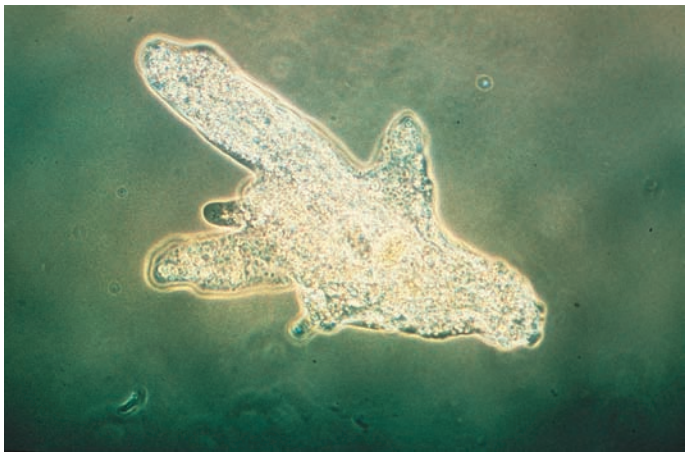
15. The pathogen shown here is a _____.

a. virus

b. protist

c. fungus

d. prion



THE PLANNER

Review your Chapter Planner on the chapter opener and check off your completed work.

11 Cancer

In June 2008, thousands of people came to Washington, D.C., to run in the 25th annual Susan G. Komen National Race for the Cure for breast cancer. The race was first held in Dallas, Texas, in 1983, when its founder, Nancy Brinker, established the event in honor of her sister, Susan G. Komen, who had died of breast cancer. Eight hundred people ran in the first race. Since 1983, in scores of cities and towns across the country, over 1 million mothers and daughters, fathers and sons, sisters and brothers, and family friends have raced, and countless millions of dollars have been raised to help support breast cancer research. Race organizers and participants are now the world's largest grassroots network of breast cancer survivors and activists, dedicated to saving lives by helping breast cancer specialists find cures and more effective treatments with fewer toxic side effects.

Breast cancer research has helped to significantly lower death rates from the disease in the past 20 years, but much more work is needed. Breast cancer is the second leading cause of cancer death in women in the United States, after lung cancer. According to the American Cancer Society, in 2008 about 182,000 women will be found to have invasive breast cancer, and more than 40,000 will die from the disease.

CHAPTER OUTLINE

Cancer Cells Develop in Distinct Ways 280

- Cancer Cells Have Certain Characteristics
- Cancer Cells Multiply and Divide to Form Tumors
- The Immune System Destroys Most Potentially Cancerous Cells
- Cancer Progresses in Stages, but Starts with One Cell

Cancer Has Many Causes and Effects 285

- Certain Genes Are Linked to Cancer
- Environmental Carcinogens Can Cause Cellular Mutations
- Viruses Can Promote the Development of Cancer
- Certain Diets May Contribute to Cancer
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- Cancer Can Strike Almost Any Part of the Body

Cancer Can Be Diagnosed and Treated Effectively 296

- Diagnosing Cancer Requires Many Tools
- Treating Cancer Is a Multistage Process
- Personal Choices Help Fight Cancer

CHAPTER PLANNER

- ❑ Study the picture and read the opening story.
- ❑ Scan the Learning Objectives in each section: p. 280 ❑ p. 285 ❑ p. 296 ❑
- ❑ Read the text and study all figures and visuals. Answer any questions.

Analyze key features

- ❑ Process Diagram, p. 282
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- ❑ Health, Wellness, and Disease, p. 290
- ❑ What a Scientist Sees, p. 295
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- ❑ Stop: Answer the Concept Checks before you go on: p. 284 ❑ p. 296 ❑ p. 302 ❑

End of chapter

- ❑ Review the Summary and Key Terms.
- ❑ Answer the Critical and Creative Thinking Questions.
- ❑ Answer What is happening in this picture?
- ❑ Answer the Self-Test Questions.

11.1 Cancer Cells Develop in Distinct Ways

LEARNING OBJECTIVES

1. **List** the characteristics of cancerous cells.
2. **Explain** which genes control cell growth and division.
3. **Outline** the response of the immune system to the cancer.
4. **Describe** the stages of growth of a malignant tumor.

Cancer is a frightening word. Several years ago, cancer passed heart disease to become the most frequent cause of death in the United States. However, because of medical advances cancer should be less frightening than it was a generation or two ago. Twenty years ago, a doctor might have said to the parents of a five-year-old diagnosed with cancer that the child would have a fighting chance of living to adulthood. Now, doctors can routinely tell those parents that their child will almost certainly live to become an adult. They can also say that the child will probably be able to do all the things his or her classmates are doing and will not miss much school because of treatments.

The good news is that five-year cancer survival rates have been inching up, from roughly 50% in 1970 to almost 70% today. The more we learn about cancer, the more it becomes a chronic illness that may recur but can be managed with proper treatment—and in some cases even avoided with lifestyle changes.

We know that our bodies produce cancerous cells each day, but most are killed by our immune system. Cancer is tenacious, but so are our bodies (and so are cancer researchers). Although frightening, this cancer cell production is a very rare event, similar to getting struck by lightning or being eaten by a shark. Our bodies contain trillions of cells dividing billions of times each day, with each division holding a chance that something can go wrong. Only a scant few mistakes creep through. Despite the fact that a few of these cells become cancerous, due to our incredibly adept immune surveillance system, barely one-third of us will develop cancer in our lifetimes.

Cancer is not a single disease. Actually, more than 100 specific diseases are lumped together under the term *cancer*. Each form of cancer requires a specific form of treatment. As we learn more about various cancers, we are continually refining treatment regimens, to the point where each individual's treatment regimen is truly a "personal" plan designed to fight a personal cancer. Medicine has moved beyond the three pillars of previous cancer therapy—surgery, chemotherapy, and radiation—to embrace such techniques as immunotherapy, anti-hormone therapy, and genetic and molecular therapy, in an effort to fight cancerous cells more precisely. The more we learn about the genetic component of cancer, the closer we come to being able to treat cancers before they occur by replacing defective genes.

Cancer Cells Have Certain Characteristics

Cancer describes a series of diseases that all have common characteristics. The most striking of these is that cancer cells lose control over their own growth. Unlike normal cells, cancer cells either disregard or don't receive the chemical signals that tell them it is time to stop dividing and die. They break away from nearby cells and begin a cycle of uncontrolled, often rapid division and replication. In general terms, cancer can be defined as uncontrolled cell replication that occurs because of a breakdown in the normal mechanisms of cell regulation.

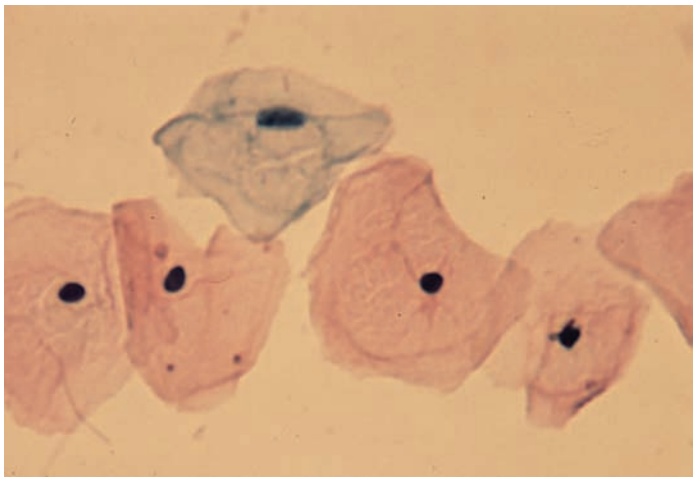
Along with this lack of growth control, all cancers have other common characteristics, as seen in **Figure 11.1**:

- Cancer cells lack **differentiation**. A cancer cell is not differentiated, meaning that it has no specified function and therefore can make no contribution to the overall functioning of a particular body part. During the usual course of development, cells must activate those genes required to produce the proteins necessary for the tissue in which they reside. For example, skeletal muscle cells must produce actin and myosin, whereas epithelial cells can shut those genes off. Because cancer cells have no homeostatic function in the body, they do not need to regulate which genes are activated or which proteins are created.

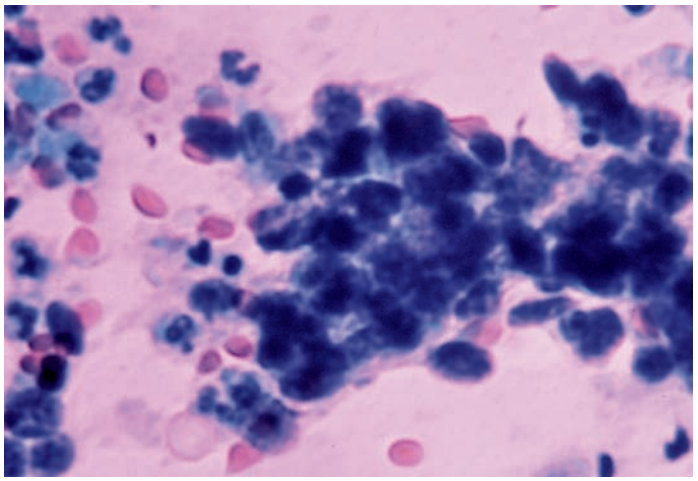
differentiation
Cellular process that causes the cell to become specialized to perform a particular function.

- Cancer cells have abnormal nuclei. Their nuclei are typically larger than those of normal cells; some take

Normal and cancerous cells • Figure 11.1



a. Normal epithelial cells of the cervix. The cell nucleus is small and located in the center, and the cell shapes are regular.



b. Cancerous cells from the cervix. The cells have very large nuclei and irregular shapes.

up most of the cell. The chromosomes of cancer cells are also abnormal: Portions of their DNA may be duplicated or deleted.

- Cancer cells have unlimited potential to replicate. Normal cells are programmed to die if their DNA is damaged or if they replicate too many times. Programmed cell death is called **apoptosis**, and cancer cells manage to avoid it. They become "immortal."

apoptosis
Programmed cell death.

How do cancer cells avoid apoptosis? Avoiding programmed cell death is a real trick, as it leads to immortality. Some people think this would be a wonderful skill to acquire; however, there are drawbacks on the cellular level. Losing the ability to perform a necessary and specific function is a high price to pay! As it is, each of our cells has both growth-stopping genes and growth-promoting genes. The growth-stoppers are called **tumor-suppressor genes**, and the growth-promoters are **proto-oncogenes**. These are often called the accelerator (proto-oncogenes) and the brakes (tumor-suppressor genes) of the cell. As with all genes, these can suffer random mutations. If both the tumor-suppressor genes and proto-oncogenes in the same cell are altered, the result could be cancer.

One of the most important and studied of the tumor-suppressor genes is named *TP53*, which gives directions for the making of a very important protein, p53. p53 works as a kind of general manager to cell functioning, halting cell division in an abnormal cell unless and until any damaged DNA can be repaired. If it cannot be repaired, the TP53 gene and its protein, p53, initiate a series of physiological changes that ultimately lead to the cell's death. If the production of functional p53 is prevented, the cell has no way to control its own destruction. Researchers estimate that more than 50% of all cancers involve something going wrong with a cell's supply of p53.

A second way in which normal cells are safeguarded from uncontrolled replication is through **telomeres**, tiny pieces of DNA located at the tips of chromosomes. Telomeres are maintained by an enzyme called **telomerase**, which the body usually stops producing soon after birth. Each time a cell replicates, a little bit of the telomere is snipped off; in laboratory experiments, a typical cell replicates 50 or 60 times before the entire telomere is gone. At that point the cell stops replicating, and eventually it wears out and dies. However, if telomerase is present in the cell, the telomere is repaired after every division, and the cell can continue to divide indefinitely. Therefore, the cell that develops the ability to maintain telomerase in its cytoplasm lives "forever" and is on its way to being a cancerous cell.

telomeres
Stretches of repeating DNA bases located at the tips of chromosomes.

Cancer cells can either have faulty TP53 genes or continue to produce telomerase, or both. If the TP53 gene is faulty or the cell continues to produce telomerase, the affected cell is able to replicate uncontrollably and rapidly. The cell achieves a kind of immortality, since it does not receive or does not respond to the signals telling it to die. It is now literally misguided and out of control.

Cancer Cells Multiply and Divide to Form Tumors

Unlimited cell division is not the only characteristic a cancer cell must have—it also needs to be able to adhere to surrounding cells. Unlike normal cells, cancer cells lose their natural inhibitions and begin to pile up on one another, forming a **tumor**. Cancer cells must be able to form tumors, which can be **benign** or **malignant**—benign if they don't expand into adjacent tissues, malignant if they do. Moles, polyps, and warts are examples of benign tumors. See Figure 11.2.

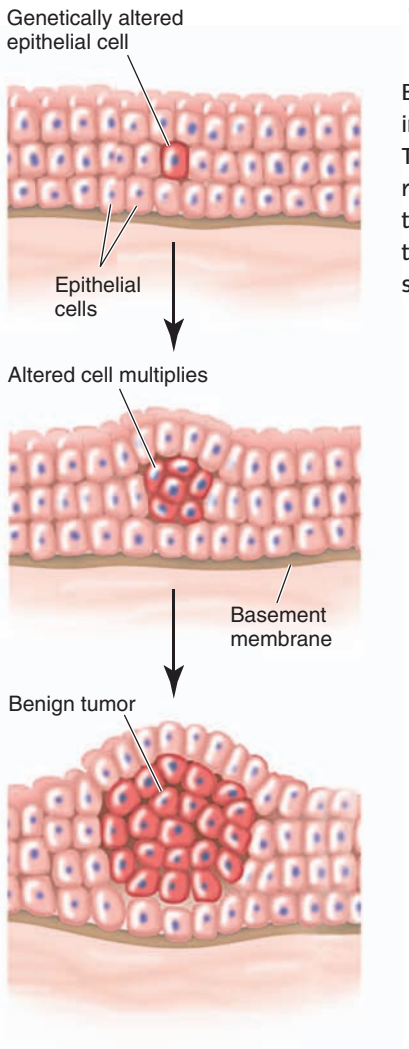
tumor A group of cancer cells.

malignant Refers to a cancerous tumor that is harmful, invasive, and able to spread.

PROCESS DIAGRAM

Benign tumor formation • Figure 11.2

THE PLANNER



Benign tumors grow in situ, or in place. They push on surrounding tissue rather than infiltrate it, and they do not metastasize, or spread.

Cancerous tumors form when proto-oncogenes mutate. Proto-oncogenes, affected by proteins called **growth factors**, stimulate cell division, whereas tumor-suppressor genes inhibit cell division. In normal cells, these two genes act in concert to make sure the cells are dividing appropriately.

growth factors Chemicals that stimulate cell growth.

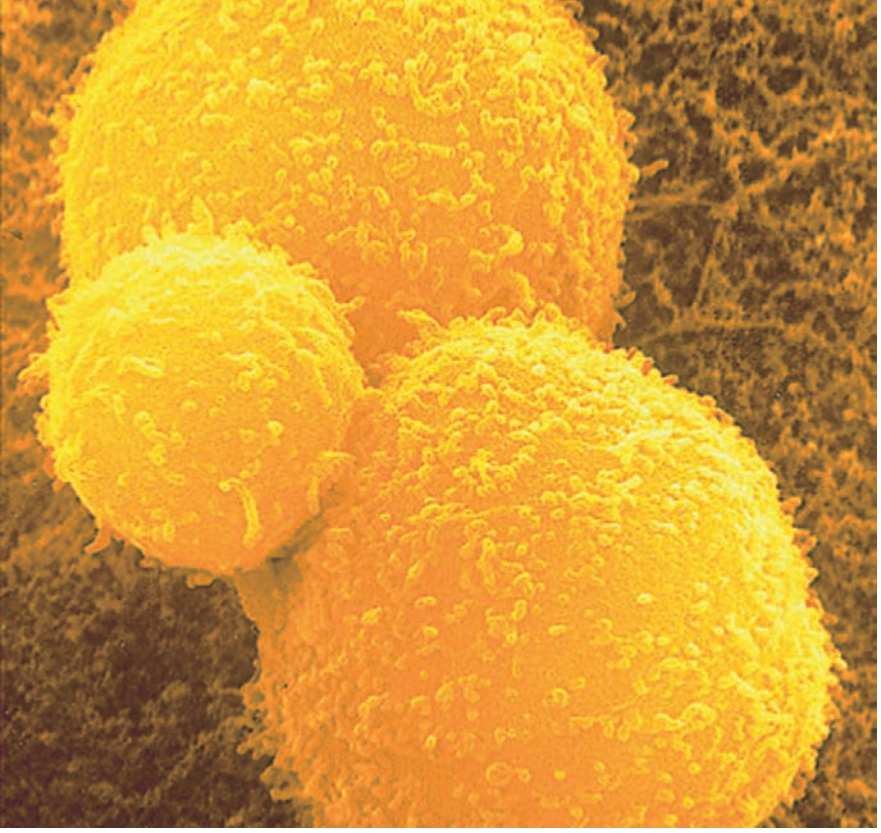
oncogenes Genes that cause cancer.

When proto-oncogenes mutate, they form **oncogenes**, or genes that cause cancer. Because there are many proto-oncogenes in each cell, it is possible to form many oncogenes in one cell. Naturally, every oncogene disrupts cellular function, so the more oncogenes that are activated, the worse off that cell will be. The opposite can also happen, and tumor-suppressor genes can mutate. Altered tumor-suppressor genes will no longer regulate the cell cycle and will not promote apoptosis. Such mutations are referred to as "loss-of-function" mutations, for obvious reasons. If a cell winds up with extra copies of oncogenes or not enough tumor-suppressor genes, or both, it has a strong possibility of developing into a cancerous tumor.

The Immune System Destroys Most Potentially Cancerous Cells

These types of mutations are occurring all the time, as DNA replicates in preparation for cell division on a continual basis. This means that our body produces cancerous cells each day. Most of them are killed off by the body's natural defense mechanisms. The immune system recognizes these cells as "other" or "nonself" and reacts to them as it would to any other foreign tissue, through the process of rejection. Many cancer cells have antigens on their surfaces that are not found on normal cells of the body. Usually, T cells and NK cells recognize these abnormal antigens in potentially cancerous cells and destroy them. Just as proto-oncogenes and tumor-suppressor genes battle each other daily to find the right balance of promotion and inhibition of cell replication, the body's defense cells and cancerous cells do battle every day. See Figure 11.3.

This is not a one-way battle, however. Cancer cells have mechanisms that allow them to avoid destruction by the immune system. Some types of cancerous cells include mechanisms that actively seek to avoid the body's defenses, while other cancers simply overwhelm the immune system



T cell attacking two large tumor cells • Figure 11.3

T cells and natural killer cells are effective in removing many potentially cancerous cells. However, these cells fail to destroy all tumor cells, so modern medical practices are working to fill in the gaps.

defenses by multiplying more rapidly than they can be killed off. It goes without saying that if the immune system is weakened, for whatever reason, cancerous cells will have a distinct advantage.

Cancer Progresses in Stages, but Starts with One Cell

All tumors start as one cell gone wild. The cancerous cell must compete with its surrounding cells for nutrients and space. If the cancerous cell has distinct advantages over its neighbors, like ways to avoid cellular apoptosis, the cell will survive and divide and those advantages will be passed on to its descendants. The cancerous descendants tend to accumulate even more mutations as they divide rapidly and without control, making their progeny even more abnormal. These mutations allow the cells to continually change with each generation. The changes make it harder for the immune system to identify these cells, and therefore make it harder for the immune system to track down and destroy them.

Cancer cells can continue to grow unchecked.

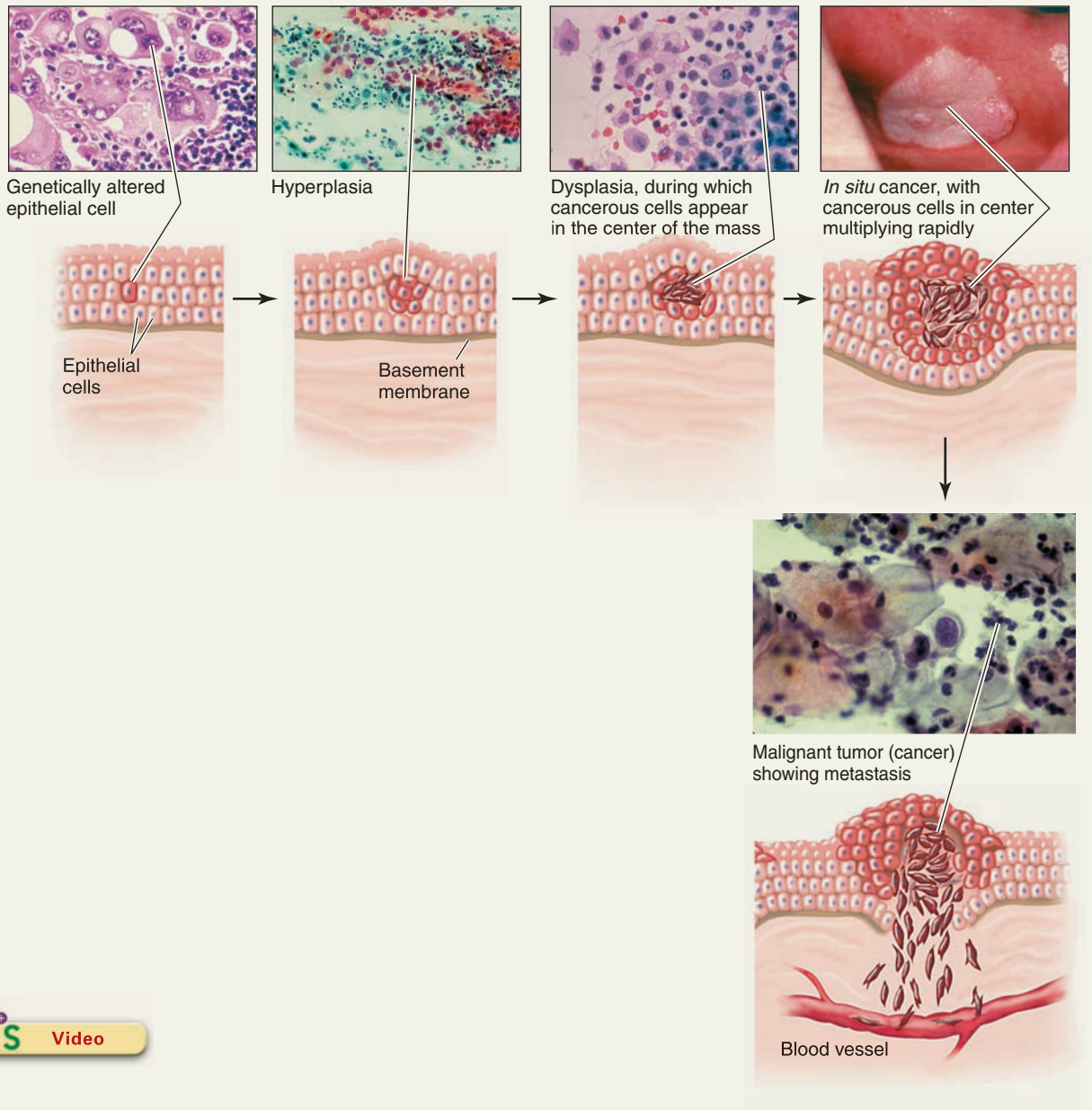
Once they have overcome the body's defenses, cancer cells can exploit their advantage and continue to grow and multiply unchecked, carrying many mutations that were all set in motion by a single mutation in a control gene. These mutated cells can then successfully outcompete normal cells for space and nourishment. If this happens, **carcinogenesis** has begun. When a malignant cancerous growth reaches about 1 million cells (approximately 1 or 2 millimeters in diameter), the cells in the interior can no longer receive enough nutrients, and they begin depositing their waste products within the cell cluster. This ball of cells is now referred to as a **carcinoma** *in situ* ("cancer in place") and, if not removed, it will need its own blood supply. The carcinoma in situ will begin producing its own growth-enhancing proteins and secreting chemicals called angiogenic compounds that will lure blood vessels into the tumor. **Angiogenesis** is the process by which new blood vessels are formed to feed a tumor. Once it has a blood supply, the tumor becomes immortal. The cells are capable of continual divisions, the tumor has a nutrient supply and a waste removal system, and it begins to crowd out the surrounding noncancerous cells. Unless it is cut out, killed with chemicals, damaged by radiation or another substance, or starved of its nutrient supply, the tumor will grow and spread until it kills its host.

carcinogenesis The process by which cancer develops.

angiogenesis The growth of new networks of blood vessels (*angio* = blood vessel; *genesis* = new creation).

Cancer tumors can invade almost any tissue.

Not only do cancer cells grow uncontrollably and adhere to surrounding cells, but they also tend to invade normal tissue. Cancerous tumors can invade any kind of body tissue, from skin and bone to organs like the lungs, liver, and intestine. Once a tumor has become firmly established in such a "primary site," cancerous cells often break away from the original mass and travel through the bloodstream or lymph. This migration of living cancerous cells from the original tumor is called



WILEY PLUS Video

metastasis The spread of cancer cells from their primary site to other sites.

metastasis, and is the process by which the original cancerous tumor spreads throughout the body. The traveling cells are deposited at "secondary sites," where other tumors may develop. These metastatic tumors may continue to grow even if the primary tumor is killed or removed. See **Figure 11.4**.

CONCEPT CHECK STOP

1. **What** are the characteristics of a cancerous cell?
2. **What** genes control cell growth and division?
3. **How** does the immune system respond to cancer?
4. **What** are the stages of growth of a malignant tumor?

11.2 Cancer Has Many Causes and Effects

LEARNING OBJECTIVES

1. **List** the four major categories of factors that cause cancer.
2. **Define** what is known about each causal factor.
3. **Explain** how cancers are classified.

What causes cancer? The question has been at the top of the cancer research agenda almost since the beginning of the "War on Cancer" declared by President Richard Nixon in 1971. In the 40-some years of research since then, scientists have determined that a number of common occurrences, ranging from viruses to hereditary factors to exposure to radiation, play a part in causing cancer. Although it is statistically impossible to say that there is a single cause for an individual cancer, we now know that many factors play a role in initiating and promoting cancer. Scientists have identified several factors that create a predisposition to cancer, initiate the development of a cancerous tumor, or promote the growth and metastasis of a cancer. Amazingly, researchers are finding that most cancer-causing mutations are the result of the body's cells accidentally damaging their own genes in the normal course of cellular respiration. During the breakdown of nutrients within the cell, a molecule breaks loose and damages the cell's own DNA. As we have noted, these mutations occur all the time, so it is clear that mutations alone are not enough to cause cancer. There must be other factors involved in causing cancer. Scientists have identified many of these factors, and have found that they fall into four major categories: heredity, environment, viruses, and diet.

Certain Genes Are Linked to Cancer

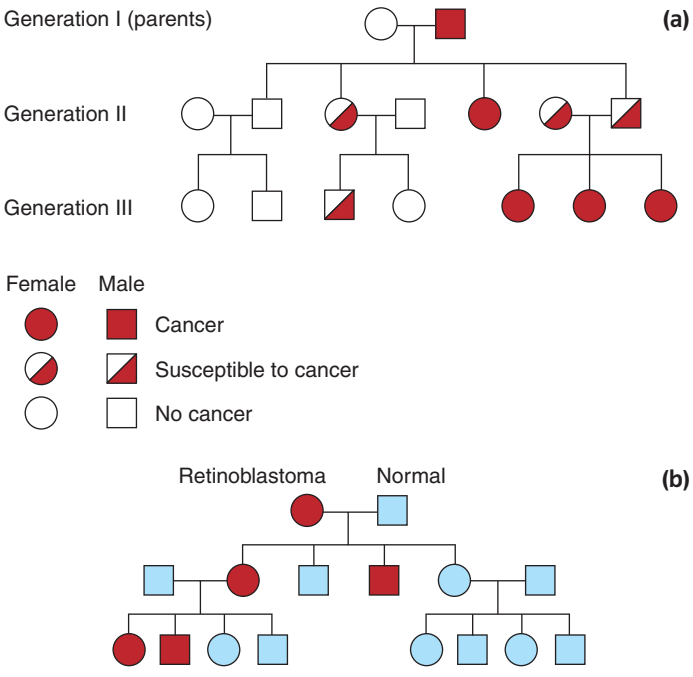
It is probably not surprising that the sequence of genes you carry on your chromosomes can affect your body's ability to ward off cancer. Scientists have found a number of genetic markers that predispose individuals to one or another form of cancer. **Figure 11.5** shows a sequence describing genetic predispositions to cancer. The earliest discovery of a genetic association to a particular cancer occurred in 1990 with the identification of a gene that, when passed to a female child, greatly increases the likelihood that she will develop breast cancer. The gene was named **breast cancer gene 1**, or *BRCA1*. A second gene, discovered later, was called *BRCA2*. Both BRCA1 and BRCA2 are tumor-suppressor genes.

While some scientists believe that any woman who carries a mutant BRCA1 or BRCA2 gene will develop breast cancer, it seems that the situation is far more complicated. If a mutated BRCA1 or BRCA2 gene is inherited from either parent, the child carries that mutated gene in every cell in her body. Because she carries two copies of every gene in her cells (one from each parent), the mutated gene will not be expressed and her chances of developing breast cancer are no higher than for the rest of the population. Only if a second BRCA1 or BRCA2 mutation occurs through the natural process of genetic mutation does the child's chances of developing cancer increase over those of the general population. If the second mutation develops in breast tissue cells, the result is breast cancer. If the mutation develops in an ovary, the result is ovarian cancer.

Other genes have been definitively linked to an increased risk of contracting particular cancers. For example, the *RB* gene has been linked to **retinoblastoma**, a cancer of the retina. RB is another tumor-suppressor gene. Both copies of the RB gene must be mutated in order to increase an individual's risk of contracting this form of cancer.

The genetics of cancer • Figure 11.5

The causes of cancer include genetic predisposition. Pedigree A is a general example, while Pedigree B is typical of retinoblastoma.



For some genes, only one mutated copy need be present to increase the risk of developing cancer. The risk of contracting thyroid cancer is greatly enhanced if the individual has a mutation in one of the two copies of the *RET* gene present in every cell. According to research from the Sloan Kettering Cancer Center, nearly everyone with one mutated RET gene develops medullary thyroid cancer.

Environmental Carcinogens Can Cause Cellular Mutations

As if the threat of naturally occurring, cancer-causing mutations were not enough, it appears that there are agents in the environment that increase our risk of developing cancer. **Carcinogens** are all around us—in the air we breathe, the water we drink, and the products we use in and around our homes. We can avoid contact with some, but not all, of these agents. Environmental carcinogens act by causing cellular mutation. These mutated genes can then be passed from parent to child in the egg or sperm, and they may then predispose the child to developing cancer. However, unlike the previously discussed mutations of oncogenes or mutator genes, some kind of **initiator** needs to be present to trigger the cellular activities and secondary mutations necessary for cancer to develop in these individuals. Some environmental carcinogens act only as initiators, whereas others act as both initiators and **promoters**.

carcinogens Environmental agents that can cause cancer.

initiator An agent that causes cancerous changes in cellular functioning.

promoters Environmental agents that increase the likelihood that an initiator will affect cellular functioning.

Some cancer researchers have estimated that more than 50% of all cancers are caused by environmental carcinogens. However, that number is much smaller if we factor in only the environmental chemicals most people think of as causing cancer—smokestack pollution and chemicals in our drinking water or food. Additionally, there is a whole host of naturally occurring chemicals that have been proven to cause cancer in research studies, including tannins found in high concentrations in teas, safrole found in cinnamon, and even one of the major flavor-enhancing compounds in black pepper. In truth, multiple factors contribute to each cancer, with environmental agents factoring in many cases.

Some environmental carcinogens • Figure 11.6

We know a good deal about individual suspected carcinogens, but we know little about their interactions with each other. We know almost nothing about their interactions with hundreds of new chemicals introduced to our environment each year.

The two most prevalent forms of environmental carcinogens are chemicals and radiation. Some chemicals and some forms of radiation can be avoided, but not all. **Figure 11.6** shows some common environmental carcinogens. Among the chemical carcinogens that are most easily avoided are those associated with smoking organic compounds. The process of burning tobacco or any other organic material causes the release of multiple chemicals. Tobacco smoke, for example, contains N-nitrosonor-nicotine, vinyl chloride, benzo[a]pyrenes, and other chemicals, each of which has been identified as a carcinogen. Even the paper used in cigarettes includes harmful chemicals that are released when the cigarette is burned. Estimates of the percentage of cancer deaths linked to cigarette smoke run from 30% to 80%. This percentage includes deaths due both to smoking and to regular exposure to smoke (referred to as "passive smoking" or "secondhand smoke," and often occurring among family members and close co-workers of smokers). Since the 1990s, legislators at the local, state, and federal levels have enacted numerous laws to reduce passive smoke exposure by limiting the amount of smoking permitted in workplaces, schools, restaurants, public transportation, and entertainment venues.

To put the relationship between tobacco smoking and cancer in perspective, only about 2% of cancer deaths are linked to exposure to industrial pollutants. The majority of these cancers occur in people who work in an industry that uses the carcinogenic substances and not in people

who are exposed to diffuse environmental pollution. Many individuals wish to remain as healthy as possible and therefore try to reduce all risks of cancer in their lives. However, it is very difficult for some individuals to reduce their risk of contracting cancer through exposure to diffuse pollution. For example, although we are all exposed to some amount of diesel fuel exhaust (which is given off by trucks, buses, and trains), people in certain jobs, such as railyard workers, diesel mechanics, and miners, are exposed to far larger amounts. Also, while we are all exposed to some amount of pesticides on the produce we eat (unless we purchase only organically grown produce), we are not exposed to nearly as much as are farmers, farm workers, and packers, as shown in **Figure 11.7**. We are all exposed to a small amount of benzene that leaches out of paints, dyes, and furniture, but those who work in paint manufacturing, tanning and dyeing, and furniture manufacturing and finishing are exposed to far more.

See *Ethics and Issues: How Do We React to Cancer Clusters?* on the next page for some examples of environmental carcinogens and how we think about them.

Pregnant women and their fetuses are especially susceptible to some kinds of industrial pollution. During periods of active cellular growth and differentiation, the fetus can be negatively affected by even minute quantities of introduced carcinogen. As a matter of public policy, Americans have to decide how to balance protecting individuals from unusually high levels of carcinogens against people's right to live, work, and play as they wish. For instance, we know that many industrial solvents are highly carcinogenic and can also cause birth defects if a pregnant woman comes into contact with them, yet we still produce and use these solvents in some occupations. Does this mean that a woman working at a job that is part of a manufacturing process using dangerous solvents must leave her job if she becomes pregnant? What rights does she have to transfer to a safer job within the same company? What obligations does the company have to her? Can a company refuse to hire women who may become pregnant for any job that requires contact with a carcinogen? What about refusing to hire people with a genetic predisposition to cancer for jobs that cause the worker to come in contact with carcinogens?

This issue is not merely an academic one. In the 1970s, some states mandated testing of African Americans for sickle cell anemia, a debilitating blood disorder that is especially prevalent among African Americans. This information was used to discriminate against African Americans in certain

A farm worker spraying a field • Figure 11.7

Even wearing protective clothing, this farmer is exposed to concentrated carcinogens while preparing and spraying pesticides. Many laborers suffer similar working conditions, often without a clear understanding of the dangers they face.

ETHICS AND ISSUES

How Do We React to Cancer Clusters?

From 1997 to 2001, doctors in Churchill County, Nevada, diagnosed 15 children with leukemia, a far higher rate of diagnosis than would be expected in a lightly populated, semirural region. Beginning in March 2000 and continuing through March 2001, the federal Centers for Disease Control and Prevention (CDC), working with Nevada health officials and university and industry consultants, conducted extensive studies of environmental conditions in the region. The goal was to see whether any environmental agent could have directly caused the statistically significant increase in cancer cases.

Since the 1970s, when a similar cancer cluster was diagnosed in Love Canal, New York, federal and state health officials have investigated a number of suspicious clusters and have found a potential link between environmental waste and increased levels of cancer. The most famous of these cases have become part of our culture through books and movies, such as *Erin Brockovich* and *A Civil Action*.

The Churchill County cluster came to light years after many other well-documented clusters, at a time when medical science had vastly increased its understanding of the genetic component of cancer. In the process of investigating this cluster, researchers uncovered new links between environmental and hereditary factors in promoting and initiating cancer. Researchers found that the soil and water of Churchill County contained elevated levels of the heavy metal tungsten, the chemical arsenic, and the breakdown product of the pesticide DDT. Despite this, the content of environmental samples taken from inside and around the homes of cancer patients did not differ from the content of samples from the homes of other members of the community. Also, tissue and fluid samples taken from cancer patients did not contain higher levels of dangerous substances than similar samples from healthy children.

After these environmental and biological samples revealed no direct link between environmental agents and the cancer cluster, researchers turned to genetic analysis. From 2003 to 2006, they conducted extensive genetic tests of both ill and healthy children. The tests showed that all the ill children had a variation in a gene known as SUOX. The SUOX gene tells the body to make sulfite oxidase, a substance that acts to neutralize unsafe chemicals. It would make sense that if this gene were not producing functional sulfite oxidase, those individuals would be less able to handle the introduction of toxic compounds. However, a number of healthy children also carried a similar variation in the SUOX gene.

Critical Reasoning Issues The researchers concluded that, although a mutation in the SUOX gene leads to an increased risk of developing cancer in the presence of high levels of certain heavy metals and chemicals, it is not inevitable that exposure will cause the development of cancer. This complicated relationship of cause and effect is a familiar one for critical reasoners.

NATIONAL GEOGRAPHIC

Think Critically

1. What other cancer clusters have been in the news, and what causes and effects were found?
2. If a company's negligence leads to cancer clusters, how much responsibility does the company bear and how much responsibility does the local, state, or federal agency responsible for environmental protection bear?
3. Sometimes an industry or company will present studies of cancer clusters, often called *meta-studies*, to prove that their product or industry practice is not carcinogenic or is only weakly carcinogenic. Should you be skeptical about the inclusion of studies that follow an exposed population for only a few years or that include as many healthy workers as possible in their study?

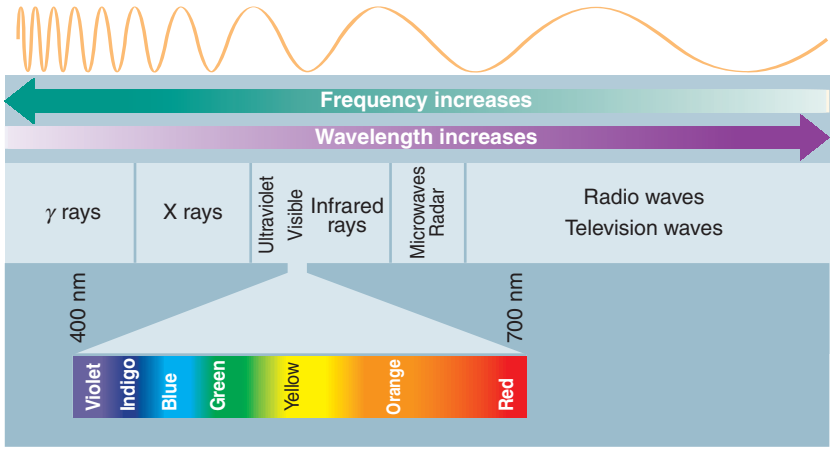
situations. For example, some insurance companies refused coverage to those who carried the gene, and employers chose not to hire those with the sickle cell genetic predisposition. In response, Congress enacted the National Sickle Cell Anemia Control Act, which withheld federal health funding from states that mandated testing and created penalties for discrimination based on sickle cell status. In the spring of 2008, Congress proposed a similar law, the Genetic Information Nondiscrimination Act (GINA), which bans discrimination in hiring based on an individual's genetic profile.

Radiation is another carcinogenic agent. Radiation takes two forms: ionizing and non-ionizing. The most prevalent source of ionizing radiation is sunlight. Figure 11.8 illustrates the electromagnetic spectrum, showing the wavelengths of various forms of light energy. Over 80% of skin cancers, especially the highly dangerous melanoma, are caused by exposure to higher-frequency ultraviolet B (UVB) rays of sunlight. People with fair complexions are more prone to sunburn than are people with darker skin, but anyone can become sunburned. Frequent sunburn, especially in childhood and young adulthood, often leads to the development of skin cancers beginning in early middle age. Although it is nearly impossible to completely avoid the sun, knowing the dangers of ultraviolet radiation has changed the habits of many people, who today are more likely to wear hats and use sunscreen than they might have been a generation or two ago.

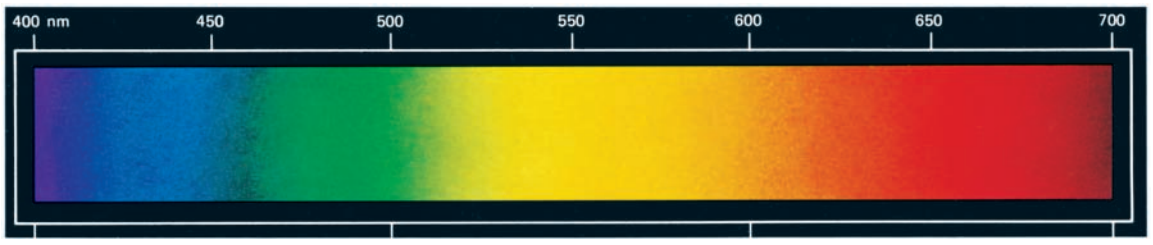
Another form of environmental radiation is radon, a colorless, odorless gas that is released by water, soil, and rocks in varying amounts and intensities in different geographic areas. Homebuyers should always have their new house inspected for radon and equipped with radon detectors. The presence of radon cannot be detected by other means; moreover, the radiation patterns of radon change over time, necessitating constant surveillance. Radon is thought to be the second leading cause of lung cancer.

Nuclear fuel, whether used to generate power or to produce bombs, has been linked to cancer. Those at risk include workers who have been exposed to radioactive materials, either while mining raw uranium or processing uranium into fuel or bomb material. Others have been exposed to radiation as a result of nuclear power plant accidents, testing of nuclear bombs, and the two nuclear bombs used in World War II. Although those affected by nuclear blasts receive extremely high doses of radiation, fortunately most of us will not experience a bombing or a nuclear power plant accident. Our exposure is more likely to result from the use of diagnostic X-rays or radiation therapy to treat cancer. The benefits of these procedures generally far outweigh the harm done by such minimal

The electromagnetic spectrum • Figure 11.8



a.



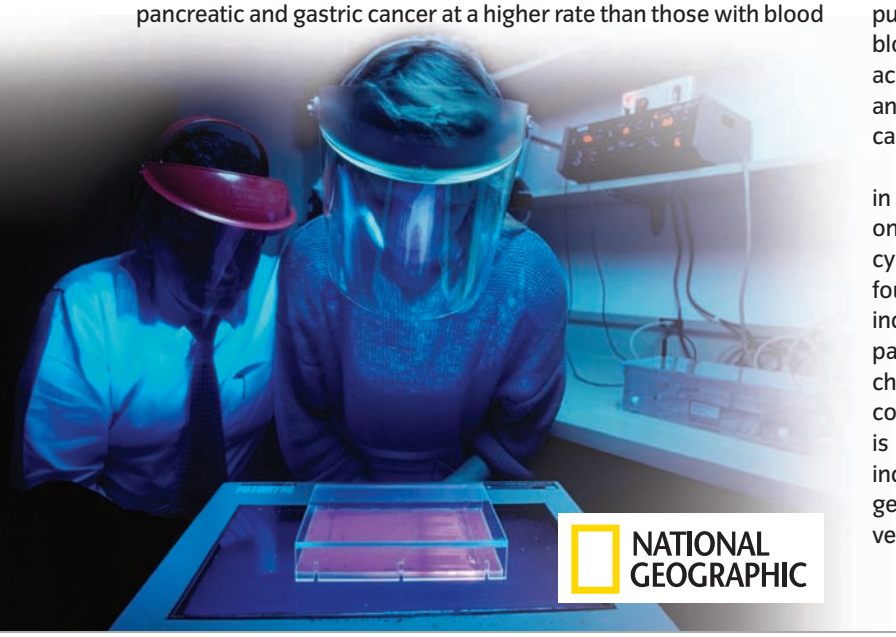
b.

The electromagnetic spectrum is divided into various sections, depending on the wavelengths of the light energy/radiation. The ultraviolet rays cause most of the damage to our skin.

HEALTH, WELLNESS, AND DISEASE

Unraveling Genetic Links to Cancer Risks

Even in the 1950s, medical professionals were aware that there seemed to be a correlation between blood type and susceptibility to pancreatic cancer. People with blood type A, AB, or B developed pancreatic and gastric cancer at a higher rate than those with blood type O. It seemed preposterous that blood type would have any real connection with cancer risks, but now scientists have uncovered a possible explanation. In August 2009, the National Cancer Institute published a study indicating there is a genetic relationship between blood type and pancreatic cancer susceptibility. Working with 14 academic centers, they compared the nucleotide sequence (A,C,T, and G) of the entire genome of 4,353 patients with pancreatic cancer to that of 4,593 control individuals.



To do this, they look for a single base difference occurring in a gene with low frequency in the population—for example, in one gene, an adenine/thymine pair may be present instead of a cytosine/guanine pair in 25% of the population. If that difference is found in 76% of the patients with pancreatic cancer, it may indicate increased susceptibility to cancer. Amazingly, pancreatic cancer patients with A, B, or AB blood type had an increased frequency of changes on chromosome 9, immediately adjacent to the gene that codes for blood type. This type of comparative genetic screening is turning up many chromosomal "hotspots," each one linked to increased risk of a specific cancer. The more we learn about these genetic links to cancer risks, the more likely we will be able to prevent the development of cancer in predisposed individuals.

radiation exposure. However, there remains a slight risk, and X-rays should not be used without a good reason.

Many people believe that the non-ionizing radiation created by electric power lines, household appliances, and cell phones is also carcinogenic. There is, however, no scientific evidence to support this notion to date.

Viruses Can Promote the Development of Cancer

Some viruses have been linked to particular cancers. Since viruses must take command of a cell's genetic machinery in order to copy themselves, they can also promote cancerous mutations. A few viruses are known to cause cancer in humans by just this process. For example, there are several forms of human papilloma virus (HPV) that together are the most common causes of cervical cancer, according to the Mayo Clinic. Although we aren't always successful in creating long-term vaccines against viral diseases because of the high rate of change in the viral coat, occasionally medical researchers are able to produce an effective one. An example is Gardasil, a recently released vaccine against HPV.

Other viruses linked to specific cancers include the Epstein–Barr virus (EBV), which is linked to both Hodgkin's and non-Hodgkin's lymphoma; the hepatitis B and C viruses, linked to liver cancer; HIV/AIDS, linked to non-Hodgkin's lymphoma and Kaposi's sarcoma; and the human T-cell leukemia/lymphoma virus, linked to T-cell non-Hodgkin's lymphoma.

How do viruses initiate cancers? We do not know exactly how viruses initiate cancer, but we do know that viruses reproduce by inserting their DNA into that of a host cell. If, in this process, the host cell's functioning is either increased or decreased, the risk of developing cancer will be increased. Viruses may also promote the development of cancer by adversely affecting the immune system and altering the natural balance between cancer cells and the cells that defend the body from them.

Together, these viruses probably account for the initiation of a very small percentage of cancers, far smaller than the percentage initiated by environmental agents. Often, the chances of developing a specific type of cancer are increased by having a genetic predisposition for that cancer. See *Health, Wellness, and Disease: Unraveling Genetic Links to Cancer Risks* to learn more.

Certain Diets May Contribute to Cancer

Statistical studies have shown that certain diets promote the growth of cancers that have been initiated either by inherited or environmental factors. Obesity has been linked with an increase of 50% or more in the incidence of colon cancer among both men and women and to an increase of 50% or more in the risk of breast and uterine cancer among women. Diets high in animal fat from beef, pork, and dairy foods have also been associated with an increased risk of colon cancer.

One 2007 study showed that colon cancer patients who continued their traditional Western diet (high in fats and red meat and low in fruits and raw vegetables) were three times as likely to have a recurrence of their cancer after surgery than colon cancer patients who altered their diet by decreasing their fat intake and increasing their vegetable and fruit intake after surgery. Somehow, the typical Western diet seemed to fuel those few cancer cells that remained in the body after surgery.

Chemicals called *nitrites*, which are converted into nitrosamines in the digestive process, are often used as a preservative in luncheon meats and other foods. A diet high in nitrites has been linked to a higher risk of cancer, as have diets high in nitrates and smoked meats, which contain chemical carcinogens similar to those found in tobacco smoke.

Fish and mollusks that feed in waters contaminated by chemicals or heavy metals often store some of these carcinogenic substances in their flesh. Therefore, it is important to limit consumption of fish caught off coastal waters, especially fatty fish, such as bluefish and bass. The Monterey Bay Aquarium has recently published a listing of seafood selections indicating which fishes are considered healthiest and which traditionally carry the highest levels of potential carcinogens. This important information is available to anyone with an Internet connection.

Excessive alcohol consumption (more than two drinks per day or on a single occasion) has also been linked to increases in many forms of cancer, especially cancers of the mouth, throat, and esophagus. Breast and liver cancers have also been linked to excessive alcohol use.

Certain Foods May Help Guard Against Cancer

While some foods are thought to promote cancer, other foods help to guard against cancer. Green, leafy vegetables contain a precursor to vitamin A called *beta-carotene*, which is an antioxidant. Antioxidant vitamins counteract the effects of the **free radicals** that are a normal byproduct of cellular metabolism. Free radicals are generally detoxified by the body's natural processes, but if that cleansing is inefficient, free radicals that build up in the body can damage other molecules, including DNA. Vitamin C, found in citrus fruit, is another antioxidant.

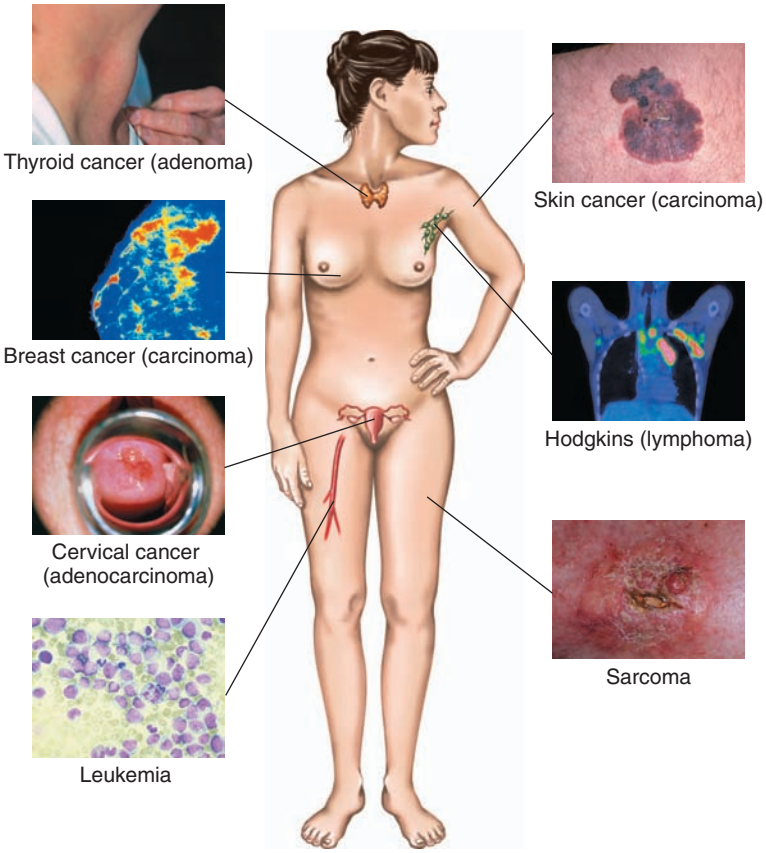
free radicals Highly reactive organic ions that have an unpaired electron, such as oxygen ions.

Cancer Can Strike Almost Any Part of the Body

Cancers are classified according to their location and the type of tissue in which they appear. See **Figure 11.9**.

Some classes of cancer • Figure 11.9

Cancers are named for the tissue from which the tumor originated. Most new cancer cases in the United States every year are carcinomas, with non-melanoma skin cancers leading the way followed closely by lung and breast cancer. Leukemias are the second most common class of cancer, but they are a distant second. According to the National Cancer Institute, NIH, total new cases of leukemia in 2008 were a mere one-thirtieth of the total new cases of carcinomas.



- **Carcinomas** are cancers of the epithelial tissues. Skin, breast, liver, lung, prostate, and intestinal cancers are carcinomas.
- **Adenomas** are cancers of the glandular tissues, such as tumors on the thyroid or adrenal gland.
- **Adenocarcinomas** are cancers of the glandular epithelial cells, such as an adenocarcinoma of the uterine cervix.
- **Sarcomas** are cancers of the connective and muscular tissues, including cancers of the bone, muscle, and fibrous connective tissues.
- **Blastomas** are cancers of the embryonic tissues, such as retinoblastoma.
- **Leukemias** are cancers involving the blood.
- **Lymphomas** are cancers involving the lymphatic system.

carcinoma Cancer of epithelial tissue.

sarcoma Cancer of soft tissue, such as connective tissue.

leukemia Cancer involving blood.

lymphoma Cancer involving the lymphatic system.

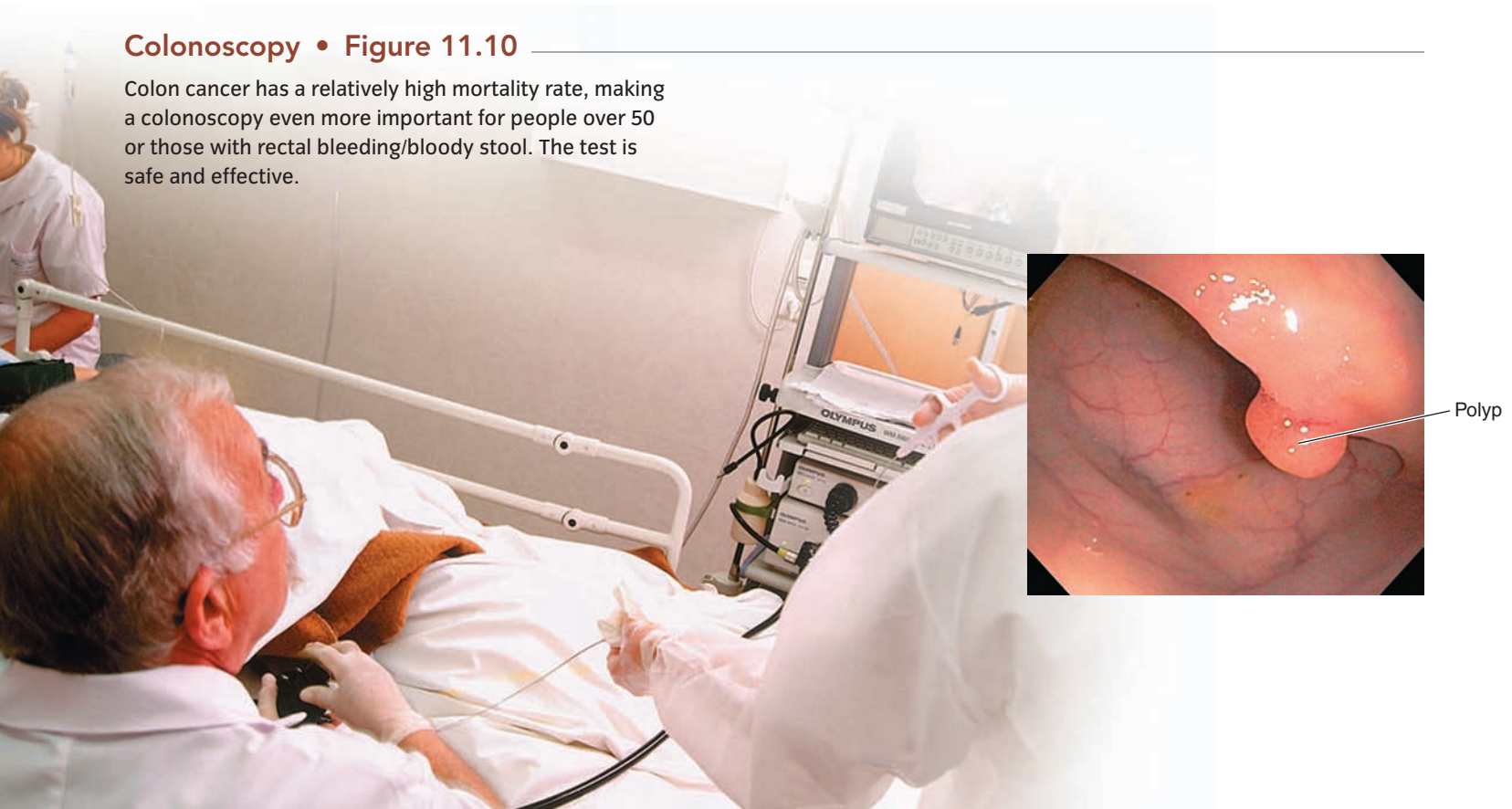
Cancer can occur anywhere in the body, but some parts are more susceptible to cancer than others. Three of the most common cancers—of the lung, the colon and rectum, and the breast—are also three of the most deadly. Survival often depends on the nature of the organ in which the cancer originates. Cancers in organs with a large blood supply, such as the lungs and liver, are usually more aggressive, and, at least in the United States, survival rates for these cancers are lower.

Lung cancer diagnosis is based on symptoms. Cigarette smoking is by far the leading factor in the development of lung cancer. All other risk factors—household, workplace, or environmental exposure to chemicals, asbestos, and radiation—pale by comparison. There is no screening test for lung cancer; it is diagnosed based on symptoms, which include persistent cough, frequent pneumonia or bronchitis, and changes in the voice. In the United States, the one-year survival rate is under 50%, and the five-year survival rate is only about 15%. Early detection improves these rates somewhat. Lung cancer causes more deaths than the next five most deadly cancers combined.

Most colorectal cancers start as benign polyps. Unlike for lung cancer, there is a screening test for colorectal cancer. Additionally, an initial diagnostic **colonoscopy** at age 50 is recommended for most people; earlier screening is recommended for those at higher risk, such as people with a family history of inflammatory bowel disease. Colonoscopy is done under sedation and involves snaking a fiberoptic tube and camera through the anus and the length of the colon, or large intestine, to the junction of the small and large intestines. See Figure 11.10. Rectal bleeding or bloody

Colonoscopy • Figure 11.10

Colon cancer has a relatively high mortality rate, making a colonoscopy even more important for people over 50 or those with rectal bleeding/bloody stool. The test is safe and effective.

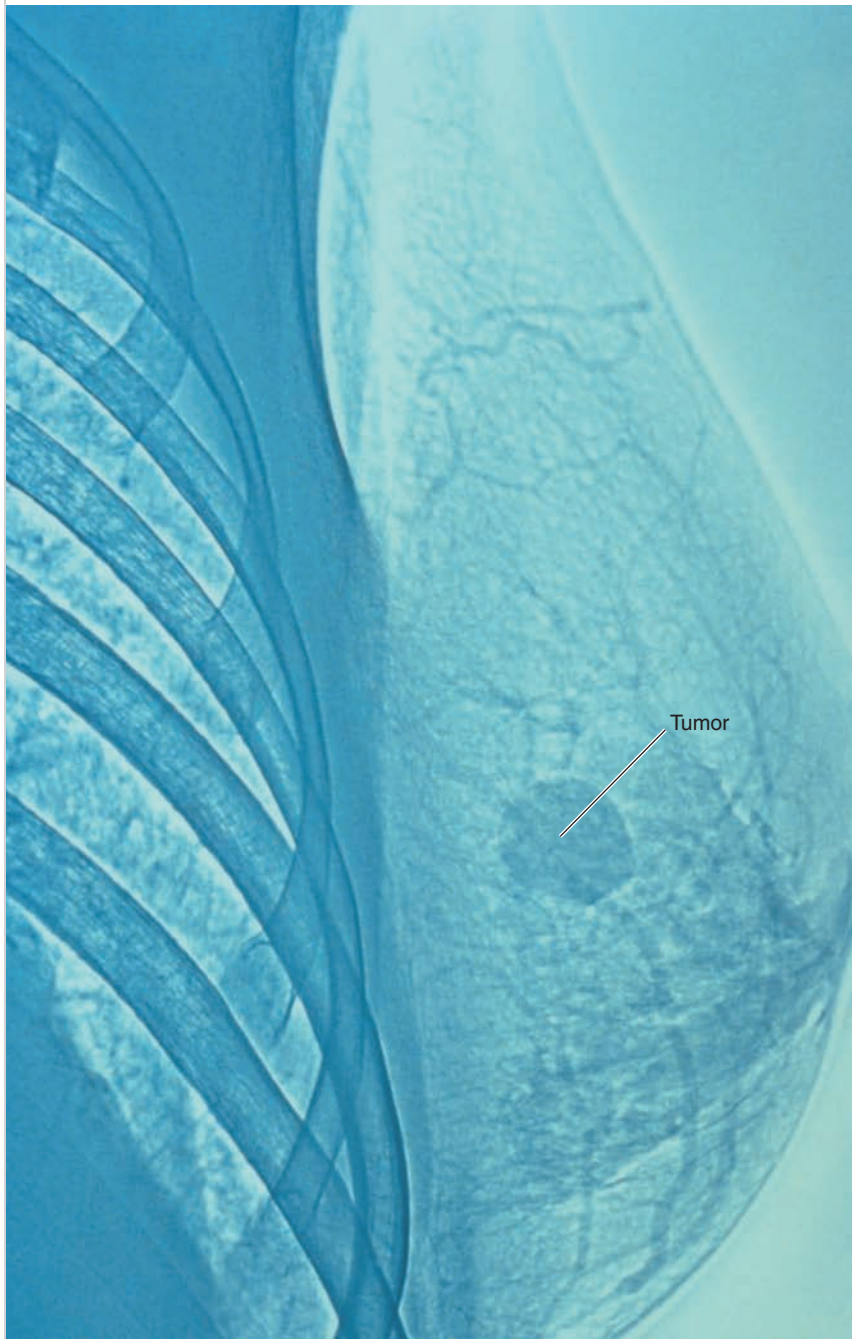


stool, even in a younger person, necessitates a colonoscopy to rule out cancer. A high-fat, low-fiber diet and a sedentary lifestyle have been linked to increased risk of colon cancer.

Most colorectal cancers start as benign polyps that protrude from the lining of the colon. Fortunately, most polyps never develop into malignancies; when they do, the process usually takes years. Early detection is important: The five-year survival rate for colon cancers is 64%, but the five-year survival rate for those in whom the cancer has spread is only 10%.

There are several risk factors for breast cancer. Breast cancer is almost solely a woman's cancer, although about 1,700 cases of male breast cancer are diagnosed each year in the United States. Age is a major risk factor: 1 in 200 women will develop breast cancer before age 40, but 1 in 26 will develop breast cancer before she reaches her 60s. Other risk factors are early menarche (the first menstrual cycle) or late menopause; obesity, especially after menopause; use of hormonal contraceptives, such as birth control pills or patches; and hormone replacement therapy after menopause.

Most breast cancer is diagnosed by means of a *mammogram*, an X-ray of breast tissue like the one shown in **Figure 11.11**. Women over age 40 are encouraged to have an annual or biannual mammogram, depending on their risk factors and family history. In recent decades, significant improvements have been made in the detection, treatment, and outcome of breast cancer. Many tumors can be removed with far less invasive surgeries than in the past. In the United States, the five-year survival rate for women with tumors that have not yet spread is 98%, and the overall ten-year survival rate is around 80%. For those with metastatic breast cancer, which has spread to the lymph nodes, the five-year survival rate is much lower.



A mammogram • Figure 11.11

Mammograms are an invaluable tool for breast cancer detection. However, they carry a small chance of both false positives (finding a growth that is not a tumor) and false negatives (missing a tumor). New imaging techniques are improving the accuracy of mammograms yearly.

There are three kinds of skin cancer. Skin cancer is the most common type of cancer for both men and women. There are three types of skin cancer: basal cell carcinoma, squamous cell carcinoma, and melanoma, as shown in Figure 11.12. Both basal cell carcinoma, which affects the basal cells of the epithelium, and squamous cell carcinoma, which affects the epithelial cells produced by the basal cells, appear as small, abnormal patches on the skin. Although they spread quite slowly if they spread at all, these cancers should be surgically removed. If these two types of skin cancer are not considered, the rate of skin cancer in the population drops dramatically from representing the most common type of cancer all the way down to between 4% and 5%.

Melanomas are very dangerous. They occur much less frequently than basal cell or squamous cell carcinomas, but they can metastasize very quickly. The five-year survival rate is 98% for individuals with melanomas that have been detected and removed; for those with melanomas that have metastasized, the five-year survival rate is under 20%.

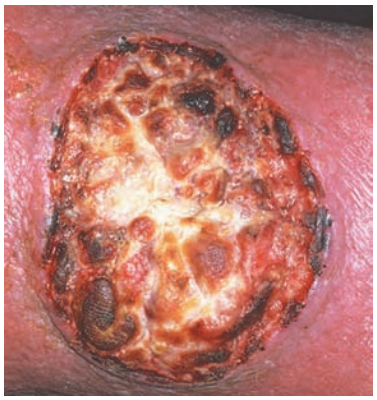
Prostate cancer occurs in men, most commonly after age 50. Because prostate cancer is quite common, men over age 50 are recommended to have either a digital rectal exam or a prostate-specific antigen (PSA) blood test, or both, annually. Symptoms of prostate cancer include difficulty or inability to urinate, blood in the urine, or pain in the pelvic area. However, these are also symptoms of an enlarged noncancerous prostate, known as benign prostate **hyperplasia**, or even of a bladder infection. Prostate cancer is a slow-growing cancer, and many men who are diagnosed with the disease after age 65 or 70 may choose not to undergo any treatment. Treatments include surgical removal of the prostate gland, radiation, and hormonal therapy. Although these treatments may seem radical, they are well worth the pain, as in the United States the 15-year survival rate for men choosing to treat their prostate cancer is over 75%. Moreover, these surgical procedures have been improved so that nerve functioning, urine control, and sexual abilities are preserved.

Leukemia is cancer of the white blood cells. Leukemia can strike anyone, at any age—even children are susceptible to this form of cancer. Unlike prostate or breast cancer, leukemia is usually a diagnosis of exclusion (that is, it is made after tests have excluded other possible conditions). The reason is that the symptoms are nonspecific, including fatigue, weight loss, and frequent infections, which are similar to the symptoms of many other diseases. A definitive diagnosis is made after a blood test and a bone marrow biopsy. See Figure 11.13. Scientists remain unclear about the factors involved in the causes of leukemia, but there are some correlations. For example, increased exposure to high levels of ionizing radiation and/or benzene has been linked to a higher rate of leukemia, although the link is statistically weaker than other accepted links between environment and cancer. The most common treatment for leukemia is chemotherapy to destroy cancerous white cells, often followed by a bone marrow transplant to replace the destroyed cells.

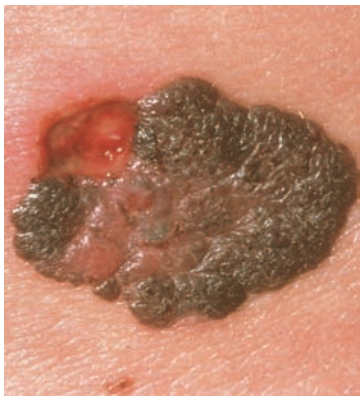
Skin cancers • Figure 11.12

Know your own skin well enough to recognize suspicious areas, and consult a medical professional if any of these descriptions apply.

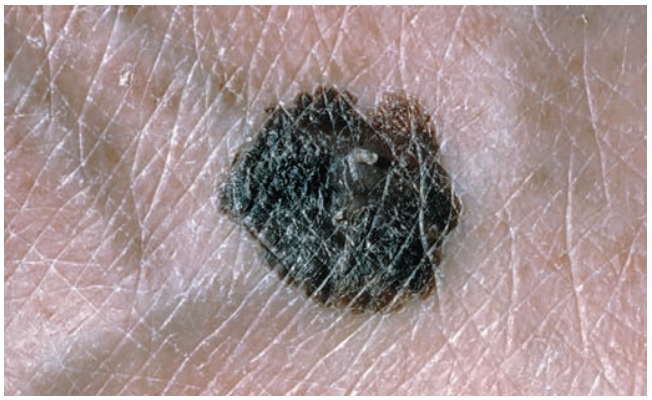
a. Basal cell carcinoma (BCC) usually develops in places routinely exposed to the sun.



b. Squamous cell carcinoma (SCC) is a tumor of the upper layers of the skin. Roughly 16% of skin cancer cases are SCC.

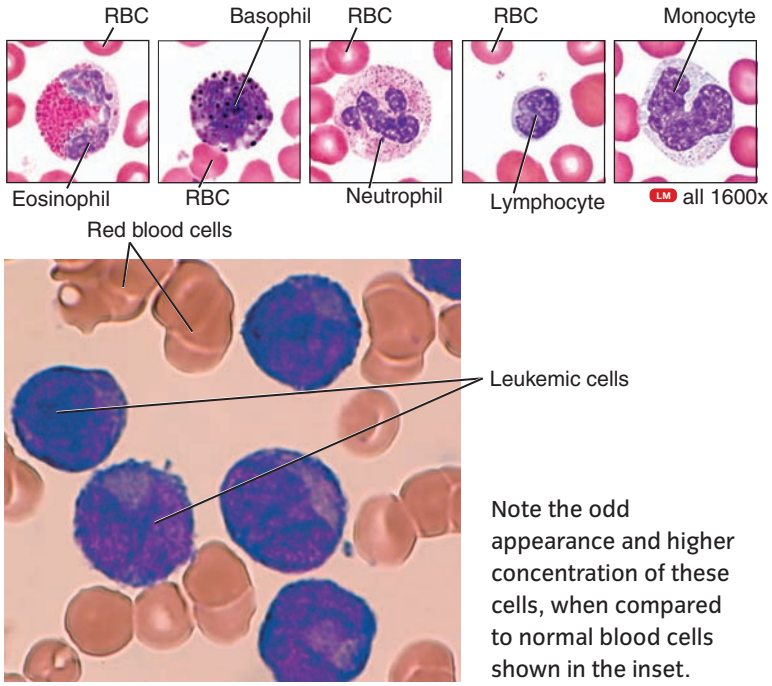


c. Melanomas are the most aggressive, and can be marked by "ABCD" guidelines: asymmetry (growing irregularly), borders that are indistinct, color that is not uniform, and diameters that are larger than those of noncancerous blemishes.



Lymphoma is cancer of the lymphatic tissue. Lymphoma is a form of cancer that attacks the lymph nodes. There are two main categories of lymphoma: Hodgkin's disease and non-Hodgkin's lymphoma. In both of these, enlarged lymph nodes are most frequently recognized in the groin, armpits, and neck. Other symptoms include intermittent fever, weight loss, and night sweats. As with leukemia, a diagnosis of lymphoma is often made after excluding more common causes of these symptoms. A weakened immune system, from HIV or human T-cell leukemia/lymphoma virus, or from immunosuppressive drugs taken by organ transplant recipients and sufferers of autoimmune diseases, increases the risk of developing lymphoma. Typically, treatment consists of high-dose radiation treatment or chemotherapy, sometimes followed by bone-marrow transplant. Newer treatments, such as specific antibodies to lymphoma cells, have shown promise. Boston Red Sox pitcher Jon Lester is a well-known lymphoma survivor. Read more about Lester in *What a Scientist Sees: Getting Back to Work After Cancer.*

Leukemia cells • Figure 11.13



Note the odd appearance and higher concentration of these cells, when compared to normal blood cells shown in the inset.

WHAT A SCIENTIST SEES

Getting Back to Work After Cancer

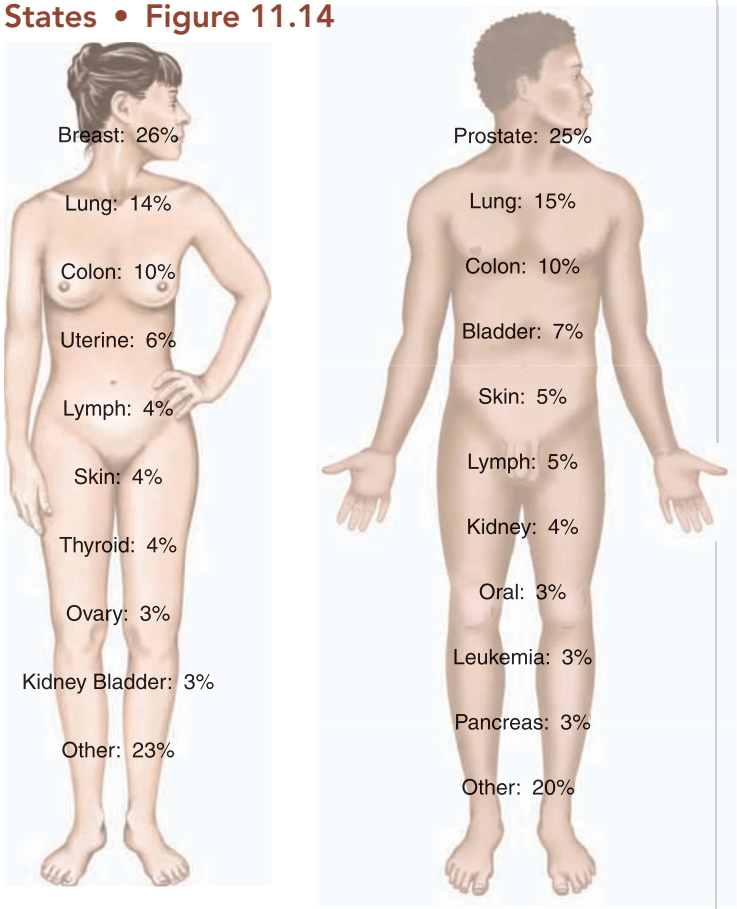
Non-Hodgkin's lymphoma was once rare, but it is now the fifth most common form of cancer in the United States. One kind of non-Hodgkin's lymphoma, called anaplastic large-cell lymphoma, strikes young males more often than others. Boston Red Sox pitcher Jon Lester was diagnosed with this type of cancer on September 6, 2006, at age 22. A very specific form of chemotherapy, combining four drugs administered every two or three weeks, succeeded in sending his cancer into remission, and a year later Lester was pitching for the Red Sox in the final game of the 2007 World Series. On May 19, 2008, Lester threw a no-hitter against the Kansas City Royals, only 18 months after being diagnosed and treated.

Younger patients have been showing the greatest improvement in five-year survival rates for lymphoma. Those survival rates have risen from roughly 50% to over 66%.

Think Critically

1. Why might a specific type of cancer—for example, anaplastic large-cell lymphoma—be more common in one gender than the other?
2. What is meant by the phrase "a very specific form of chemotherapy"? How can chemotherapy be tailored to one specific cancer?

Types and frequency of cancer in the United States • Figure 11.14



Other, less common cancers occur in the liver, kidney, pancreas, bladder, and reproductive organs. Brain cancers are infrequent but are usually fatal after a short time. A **primary cancer** does not usually form in the brain; brain cancer is usually a sign of metastatic disease that has spread from a primary cancer of the breast, colon, or lung. It is very difficult to treat brain cancers, since cancerous tissue must be totally separated from healthy tissue in order to maintain the highest possible level of brain functioning. See **Figure 11.14** for types of cancer and their rates of frequency.

primary cancer The original site of tumor development; can metastasize to form secondary cancers.

The incidence of most cancers increases with age. As we age, our risk of cancer increases. With increased life expectancies across the population comes an increase in the number of new cancer diagnoses and cancer deaths each year. Although it is tempting to look at statistics over time and determine that not much progress has been made in the fight against cancer, that would be an error. Long-term survival rates for many cancers continue to rise, and the seeming lack of progress in defeating cancer is actually due to an increasing proportion of cancer cases being diagnosed in the elderly. Because these people are advanced in age, and perhaps not physically able to withstand the rigors of surgery or chemotherapy, they often choose not to treat the cancer. In truth, medical science has made incredible advances in treating this series of diseases, and there are many exciting new techniques on the horizon.

CONCEPT CHECK STOP

1. **What** are the four major categories of factors that cause cancer?
2. **What** is known about each causal factor?
3. **How** are cancers classified?

11.3 Cancer Can Be Diagnosed and Treated Effectively

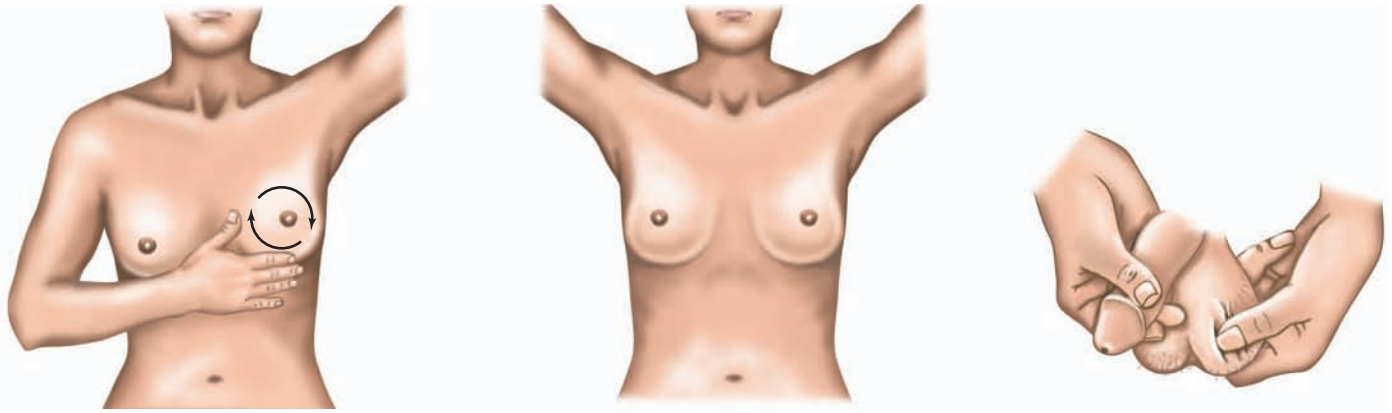
LEARNING OBJECTIVES

1. **List** the most common ways in which cancer is diagnosed.
2. **Define** the difference between traditional and newer approaches to treating cancer.
3. **Describe** the steps individuals can take to help remain cancer-free.

Although some cancers are easy to detect and diagnose, others require more thorough investigation. Some are diagnosed based on a set of symptoms, and others can be detected through routine screening. When diagnosed, however, all cancers can be treated. There are often a few different

Self-examinations by men and women • Figure 11.15

Self-examination is an important first step in cancer identification and control. Guidelines such as these can be obtained from your physician and should be followed routinely.



Shower check for breast self-exam | Mirror check for breast self-exam | Shower check for testicular self-exam

methods of treatment available, and the choice of how best to proceed rests with the patient and the attending physicians. Together, they consider the potential effectiveness of conventional and experimental treatments in extending and improving the quality of life for each individual patient. What works for one person may not be acceptable for the next.

Diagnosing Cancer Requires Many Tools

There are four ways to make a definitive diagnosis of cancer:

- Screening tests
- Imaging
- Tumor enzyme tests
- Genetic tests

There are several routine screening tests. Routine screening tests include manual self-tests, manual tests performed by a doctor or other health care provider, and visual examinations. The self-tests are important, because women performing breast self-examination and men performing testicle self-examination often find irregular lumps in these organs. On further medical examination, many of these turn out to be benign, but some are found to be cancerous. Because early detection is key to surviving these cancers, self-tests are literally life-saving activities. Figure 11.15 presents accepted methods for performing these self-examinations.

We all know that good health care includes routine physical examinations by a medical professional. Cancer screening is built into these exams. Part of a full physical examination for a man includes a testicular examination by the provider. For men over 50, the physical should include a digital rectal examination of the prostate. For women, a full physical examination includes a manual breast examination. The American Cancer Society recommends that women between 20 and 40 have a manual pelvic exam performed at least once each three years, and annually after age 40, along with a manual breast examination by a provider.

At the same time that your medical professional is examining your blood pressure and heart and lung sounds, he or she is also screening for cancers. A physical examination includes a visual examination for skin cancers of areas commonly exposed to the sun (neck, face, scalp, behind the ears, forearms, and hands). A manual examination of lymph nodes of the neck, armpit, and groin can also be performed. A digital rectal exam and card smear for occult blood in the stool should be performed every year after age 50, beginning earlier for those with risk factors for colorectal cancer. If any of these manual or visual exams reveals abnormalities, further tests should be performed to determine whether the abnormality is cancerous.

Some screening requires the use of various instruments, and therefore may be scheduled for a separate doctor's visit. For instance, it is recommended that women have a Pap smear performed by a provider annually beginning at age 18 or at the onset of sexual activity. The Pap test examines cervical cells for cancer or precancerous changes (known as **dysplasia**). A flexible **sigmoidoscopy**, which examines just the final portion of the colon, or a full colonoscopy, should be performed

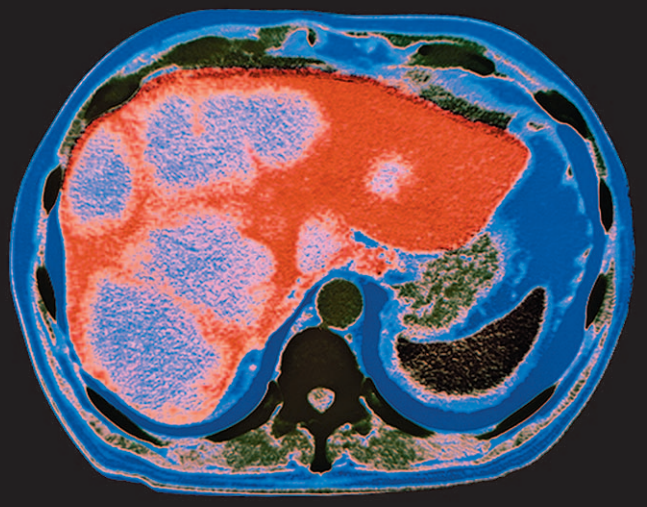
every five years beginning at age 50, and more frequently if the individual has a family history of colorectal cancer or polyps or has inflammatory bowel disease.

The mammogram is a key diagnostic tool. The mammogram, a special X-ray technology for breast imaging, is perhaps the most significant improvement in cancer diagnosis in recent history. Mammograms can detect cancerous tumors that are too small or too deep in the breast tissue to be detected in a manual examination. It is recommended that women have their first mammogram between ages 35 and 40 with annual mammograms beginning at age 40. Breast cancers diagnosed at an early stage can often be removed in a procedure that spares essentially all breast tissue.

Cancer specialists use a wide variety of imaging techniques. In addition to mammography, simple X-rays can show large anomalies and masses in soft tissues, such as those associated with lung cancers. Doctors can also use a host of other imaging techniques to diagnose cancer; one technique is shown in **Figure 11.16**. Computerized axial tomography (CAT or CT) scanning uses computerized analysis of continuously scanning X-rays to create a "cross section" of the area being scanned. This scan depicts organs and any tumors present in three dimensions. From this computer-generated image, a physician can infer a tumor's size and position relative to body organs. Magnetic resonance imaging (MRI) is particularly helpful in pinpointing and identifying tumors in connective tissues as well as tumors of the brain or spinal cord. Ultrasound uses high-frequency sound, which bounces off tissues of different densities at different rates, helping to distinguish between healthy tissue and tumors. It can provide a visualization of the size, shape, and location of tumors in the prostate, ovary, kidney, pancreas, and intestinal tract.

Liver cancer • Figure 11.16

This X-ray image with false color added shows the axial section of an abdomen with a cancerous liver. The liver is shown in red, and the cancerous liver tumors are shown as lighter sections on the liver.



Tumor markers and genetic tests can also be used to diagnose cancer. Tumor markers are chemicals produced by the body in response to the development of a tumor. When they are present in the blood, they "mark" or indicate the presence of a tumor. For example, prostate-specific antigen (PSA) is produced by prostate cells. At present, it is the only tumor marker that can be confidently used to make a diagnosis of cancer. Other tumor markers can be used to determine whether certain cancers have spread or recurred after initial treatment.

Currently, genetic tests can only determine whether an individual has a predisposition to cancer. Genetic testing cannot determine the presence of a growing tumor in the body. Recall that genetic testing can identify a woman's susceptibility to breast cancer by identifying mutated BRCA1 and BRCA2 genes. However, DNA analysis of released substances, such as urine and saliva, can sometimes identify gene mutations associated with certain cancers. For instance, cell mutations associated with lung cancer can sometimes be found in cast-off cells released in sputum; mutations associated with bladder cancer can sometimes be found in cells floating in urine; and mutations associated with colon cancer can sometimes be found in cells removed from the colon along with the feces.

Treating Cancer Is a Multistage Process

Cancer treatment has long focused on killing or removing the primary tumor and then attacking any metastatic tumors that may be present. In following this general procedure, there are three standard treatments for cancer:

surgery, radiation therapy, and chemotherapy. Because of the "sledgehammer," whole-body approach that these techniques employ, they are often called the brute force methods. Fortunately, there are also some newer, more delicate forms of cancer therapy that reflect the fact that cancer is actually many different diseases. These new methods usually use one of three refined techniques for controlling cancer:

- Attacking the tumor cells with specifically designed or selected immune cells or antibodies. This is called immunotherapy.
- Crippling the proteins that promote the cancer.
- Cutting off the blood supply to the tumor—this is called anti-angiogenesis.

These highly targeted therapies can either identify cells more precisely so that the killing treatment is applied only to cancerous cells, or block the signals that cause cancerous growth while not affecting the growth of normal body cells. These methods are called "intelligent" because they are targeted so precisely. There are also other types of treatment, often experimental, that include genetic therapy, magnetism, and phototherapy.

Surgery is still a key tool in fighting cancer. Surgical removal of cancerous tumors was performed even before the discovery of anesthetics. Surgery is the logical solution to a growth, especially one with easily identified borders—simply remove it! If a cancer appears to be contained in one small area, it is referred to as *in situ*. If detected early, completely localized *in situ* cancers, such as basal cell and squamous cell skin cancer, as well as some colon and other cancers, can be removed surgically with no follow-up treatment. However, even if it appears that a cancer is *in situ*, most cancer specialists—**oncologists**—will recommend either radiation therapy or chemotherapy after surgery to kill any cells that may have broken away from the primary tumor or been left behind after the removal of the tumor.

oncologist
A physician who specializes in the treatment of cancer.

Radiation can be deadly to dividing cells. Radiation was first employed as a medical aid soon after the discovery of X-rays in 1895. It is deadly to cells that are dividing because it damages DNA, and damaged DNA in cells typically prevents cellular divisions and leads to cell death through apoptosis. Radiation therapy is generally used if the cancer has spread from its original site but is still localized—for example, radiation may be used as a secondary treatment during breast cancer recovery if lymph nodes removed during surgery show no evidence of metastasis. In that case, radiation is used to ensure that no cancerous cells remain to begin a new tumor. Radiation is also used as the primary therapy for those cancers for which surgery is especially difficult (such as cancers of the larynx or brain) or may have undesirable side effects (such as prostate cancer).

Unfortunately, radiation does not distinguish between cancer cells and the cells of healthy tissue surrounding the cancer being irradiated. For that reason, it is one of the "sledgehammer" methods, killing every cell in its path. Depending on where the radiation beam is aimed, there may be various localized side effects, such as hair loss, irritated skin, and even blistering burns at the treatment site. Often, there are also systemic side effects, including dry mouth, fatigue, and nausea. Both local and systemic side effects generally disappear soon after treatment is ended.

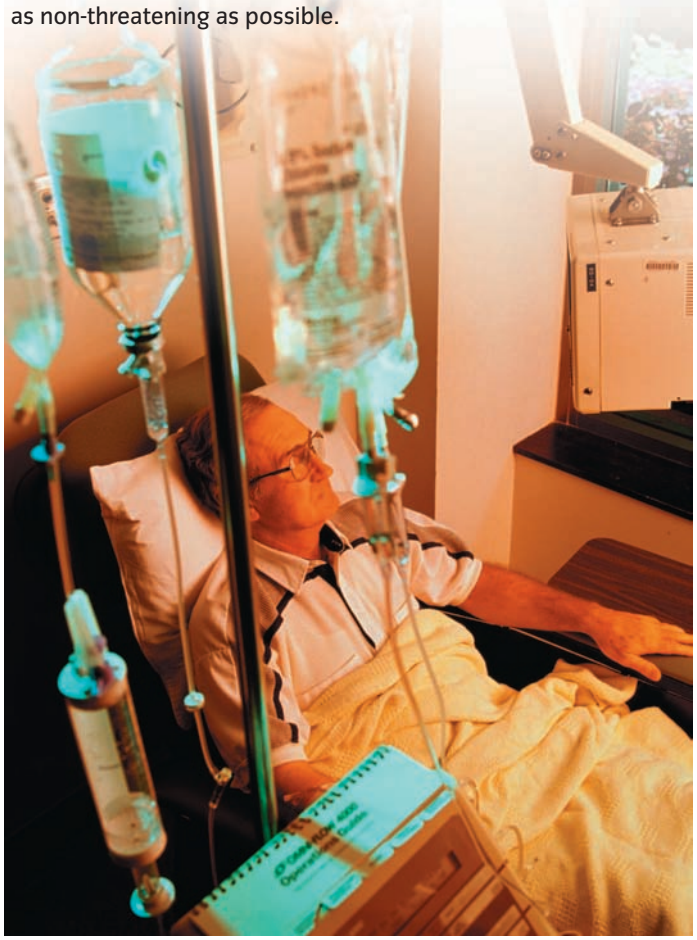
Chemotherapy disrupts cells throughout the body. Chemotherapy uses compounds that specialize in killing fast-growing cells, so it is used to attack cancers that have spread. Unlike radiation, which interrupts cell growth only where the radiation beam is aimed, chemotherapy interrupts cell growth throughout the entire body. These drugs will prevent cell division in normal healthy cells as well as cancer cells. The hope is that the growth of the cancerous tumor will be stopped before the drug causes death of healthy organs. Cancer drugs given either orally or by infusion travel throughout the body and damage rapidly dividing cells wherever they are (think attack squad with general killing orders). Some drugs damage cellular DNA; others interfere with DNA synthesis; and still others attack cancerous cellular processes—all with the aim of killing those quickly dividing cancer cells. Different drug "cocktails" are created to attack different types of cancers, with the hope of killing cancer cells while killing or damaging as few healthy cells as possible. Using many different chemicals also prevents the cancer from developing a resistance to one particular medication. The side effects of chemotherapy are the same as those of radiation: nausea and lack of appetite, fatigue, hair loss, and dry mouth, as well as anemia due to the killing of red

blood cells and reduced immune system functioning due to the killing of white blood cells. See **Figure 11.17** for an example of a chemotherapy infusion session.

Bone marrow transplants are another tool. Bone marrow transplants are sometimes performed in conjunction with chemotherapy or high-dose radiation therapy that destroys fast-dividing bone marrow cells. If possible, a bone marrow transplant is undertaken using a process called *autotransplantation*. Healthy bone marrow is located within the skeleton of the cancer patient (not all of the bone marrow is diseased even in cancers of the blood, such as leukemia). The healthy marrow is removed from the patient prior to treatment, and the stem cells that will form red and white blood cells are harvested and stored. After high-dose radiation therapy or chemotherapy has destroyed the patient's remaining bone marrow cells, the stored stem cells are transplanted back into the patient, where they begin to make new, healthy blood cells again. In cases such as sickle cell anemia, where all of the bone marrow carries the disease-causing gene, marrow will be transplanted from a closely matching donor.

IV is the typical chemotherapy delivery method • Figure 11.17

Chemotherapy is often a customized combination of drugs, delivered via IV. Some of the drugs in the cocktail cut down on the debilitating side effects of the other drugs. More effort is now being devoted to making the chemotherapy experience as non-threatening as possible.



Immunotherapy boosts the immune system. When cancer occurs, it indicates that the body's immune system is failing to kill cancer cells or is failing to kill them faster than they are reproducing. The goal of immunotherapy is to boost the immune system in an effort to help it fight the cancer more effectively. This is done in one of two ways: either by assisting in the killing of the cancer cell through creating vaccines against the cancer or by increasing the amount and activity of certain types of killer cells. Adding compounds, such as interleukin-2, interferons, and tumor necrosis factor, will assist the body's natural immune cells in fighting the disease.

Anti-angiogenesis drugs can starve a tumor. When cancerous tumors reach a certain size (about 1 to 2 million cells), angiogenesis begins. The tumor develops its own blood supply through the formation of new blood vessels. Researchers are currently studying a number of drugs that stop the process of angiogenesis, stopping the formation of these new vessels and essentially starving the tumor of nutrition. In theory, once the tumor runs out of nutrients, it should shrink and die. Also, without a blood supply the tumor cells cannot remove their waste products, resulting in toxic buildup and further cell death.

Genetic therapy holds great promise. Since the 1960s, scientists have known how genes work. Since the 1980s, they have been able to introduce genetic material into organisms to change them. This process has been done most often in agriculture, in order to create food products that are more robust or produce larger yields. Even with the lessons learned from repeated successes in altering the genetic makeup of agriculturally significant crops, correcting genetic mutations that cause disease has proven to be much more difficult. Gene therapy is still mostly the stuff of science fiction. Amazingly, in 2008, scientists at the University of Iowa and the Children's Hospital of Philadelphia announced that they had successfully used genetic therapy to correct a type of inherited blindness. Currently, work is progressing on genetic therapies for diseases that are caused by only a few genetic mutations. Unfortunately, this does

not include most cancers. Cancer gene therapy is rendered almost incomprehensibly complicated by the sheer number of genetic mutations that must be corrected and also by the complex relationship between the mutation and later promotors of disease. Despite these seemingly insurmountable obstacles, scientists continue to hope that by changing the genetic structure of cells they can reduce the incidence of certain types of cancer.

Magnetism and phototherapy are in the early stages of experimentation. Magnets may hold a key to directed cancer treatments. Powerful magnets are being experimented with in an attempt to target chemotherapy more precisely. As you know, magnets attract metal. In experiments with liver cancer, tiny metallic beads coated with chemotherapy drugs are injected into the patient. Powerful magnets are then positioned directly over the tumor, in the hope that their magnetic force will pull the drug-coated beads deeply into the tumor tissue.

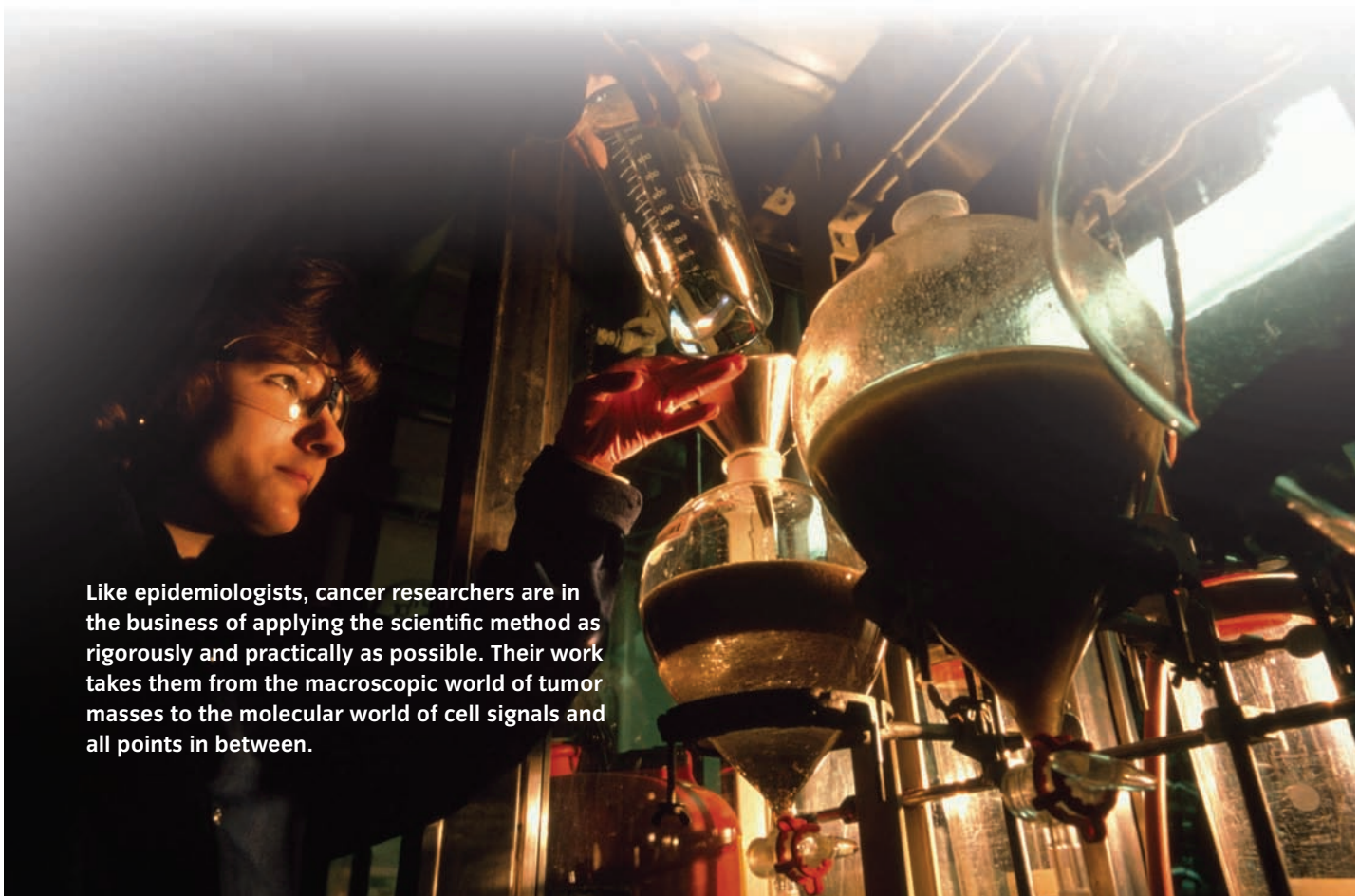
Lasers and light-sensitive drugs are being used in a similar fashion to insert chemotherapy deep into tumors embedded in organs. The patient receives light-sensitive drugs that are drawn into the tumor cells in the usual fashion; they are carried through the bloodstream and eventually find their way to the tumor. The difference between these drugs and previously discussed chemotherapy is that the light-sensitive drugs are inactive as they travel the body. Laser light directed at the tumor and focused to a particular frequency sets off a chemical reaction in the drugs that enhances their ability to kill tumor cells.

Personal Choices Help Fight Cancer

We know that personal choices matter in every area of our lives. There is mounting evidence that our personal choices increase or decrease our risks of getting cancer.

We need to support cancer research and cancer awareness. Every year, scientists learn more about cancer. As a result, people who develop cancer are able to live longer, healthier, and more rewarding lives after diagnosis and treatment. From the time we print this to the time you read this, thousands of cancer professionals will have put in millions of additional hours improving our knowledge and our odds of living well should we develop cancer. It is important that we all support research into cancer prevention and treatment. It may save our lives. See **Figure 11.18**.

Cancer researchers at work • Figure 11.18



Like epidemiologists, cancer researchers are in the business of applying the scientific method as rigorously and practically as possible. Their work takes them from the macroscopic world of tumor masses to the molecular world of cell signals and all points in between.

I WONDER...

How Can I Lower My Cancer Risks?

WILEY PLUS Video

- *Don't use tobacco*. Tobacco, especially when smoked but also when chewed or "dipped," is the most frequent cause of preventable cancers. Research shows that tobacco use leads to cancer and, in combination with environmental and other hazards, greatly magnifies the chances of developing cancer.
- *Be careful about exposure to sun*. As the protective layers of ozone have been depleted by pollution and greenhouse gases, the sun's ultraviolet rays have become more dangerous than ever before. Use sunscreen or sunblock liberally, and wear protective clothing whenever you go out in the sun.
- *Eat a healthy diet*. Such a diet is low in trans- and saturated fat, which comes primarily from animal products, and includes lots of vitamins A and D. Eat whole grains instead of processed foods. Fresh fruits and vegetables, especially green leafy vegetables, are high in fiber and potentially cancer-fighting agents.

- *Exercise in order to control weight*. Try to build lean muscle mass, and reduce accumulated fat tissue. There is evidence that fat cells can release enough inflammatory chemicals to stimulate the growth of some cancer cells.
- *Conduct regular self-exams*, and have regular complete check-ups during which a doctor or other health-care provider conducts a thorough visual and manual cancer screening.
- *Try to limit your exposure to environmental toxins*. At home, at work, and at school, take available precautions if needed—wear protective equipment, and wash thoroughly immediately after exposure to any toxins.

We need to be aware of the ways our lifestyles affect our cancer risks. You can't do anything about your genetic makeup. However, you can engage in certain behaviors that will reduce your chances of developing cancer, as seen in *I Wonder… How Can I Lower My Cancer Risks?*

CONCEPT CHECK STOP

1. **What** are some ways to diagnose cancer?
2. **How** have cancer treatments changed in the past 20 years?
3. **What** steps can individuals take to help them remain cancer-free?

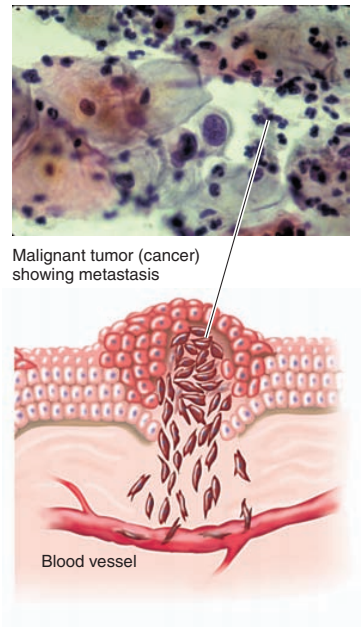
Summary

THE PLANNER

1 Cancer Cells Develop in Distinct Ways 280

- Cancer is uncontrolled cell replication that occurs because of a breakdown in normal cell regulatory mechanisms.
- Cancer cells lack **differentiation**, have abnormal nuclei, and have an unlimited potential to replicate.
- **Carcinogenesis** occurs when cancer cells outcompete normal cells for space and nourishment, forming a malignant **tumor** that is fed by **angiogenesis**. If the cancer cells spread beyond their original tumor site, they have **metastasized**, as shown.

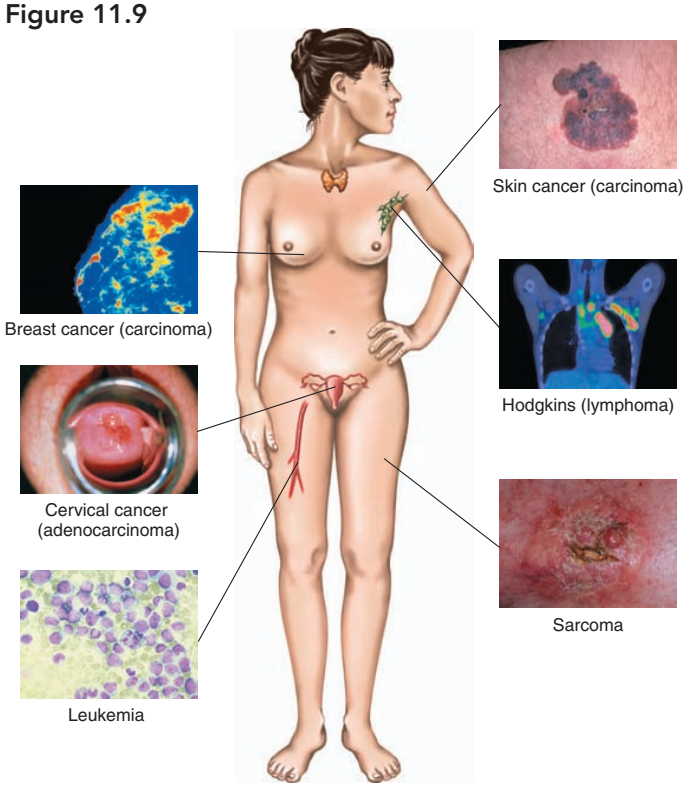
Figure 11.4



2 Cancer Has Many Causes and Effects 285

- The causes of cancer fall into four categories: heredity, environmental agents, viruses, and diet.
- The two most prevalent forms of carcinogens are chemicals and radiation.
- Cancers are classified according to their location and the type of tissue in which they first appear, as shown in the illustration. **Carcinomas** are cancers of the epithelial tissues; skin, breast, liver, lung, prostate, and intestinal cancers are some examples of carcinomas. **Adenomas** are cancers of the glandular tissue, such as tumors on the thyroid or adrenal glands. **Sarcomas** are cancers of the connective tissues, including cancers of the bone, muscle, and fibrous connective tissues. Blastomas are cancers of the embryonic tissues, such as retinoblastoma. **Leukemias** are cancers involving the blood, and **lymphomas** are cancers involving the lymphatic system.

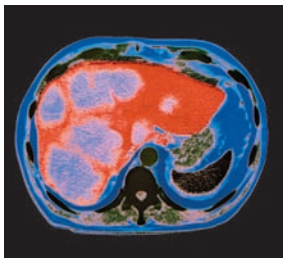
Figure 11.9



3 Cancer Can Be Diagnosed and Treated Effectively 296

- There are four traditional ways to make a definitive cancer diagnosis: screening tests, imaging (shown here), tumor enzyme tests, and genetic tests.
- Treating cancer is a multistep process. Cancer treatment has long focused on killing or removing the primary tumor and then attacking any metastatic tumors. There are three standard treatments for cancer: surgery, radiation therapy, and chemotherapy. There are also newer forms of cancer therapy that reflect the fact that cancer is many different diseases. These "intelligent" approaches include immunotherapy, anti-angiogenesis drugs, genetic therapy, magnetism, and phototherapy.

Figure 11.16



Key Terms

- angiogenesis 283
- apoptosis 281
- carcinogenesis 283
- carcinogens 286
- carcinoma 292
- differentiation 280
- free radicals 291
- growth factors 282
- initiator 286
- leukemia 292
- lymphoma 292
- malignant 282
- metastasis 284
- oncogenes 282
- oncologist 299
- primary cancer 296
- promoters 286
- sarcoma 292
- telomeres 281
- tumor 282

Critical and Creative Thinking Questions

1. A manufacturing plant in the aerospace industry employs 4,500 workers. In the past five years, 16 employees have been diagnosed with cancer, 11 women and 5 men. Twelve of the 16 are shop floor employees, and the other four work in offices. All of the individuals are between 45 and 60 years old. What other things would you like to know about these individuals to help determine whether there is a link between their work conditions and their cancer?
2. Explain the value of genetic testing and genetic counseling as it relates to cancer. Without a way to treat genetic mutations that increase the risk of developing cancer, what is the value to an individual of knowing that he or she has a particular genetic mutation?
3. Treating cancer is expensive, and there are ways in which individuals can reduce their likelihood of developing cancer—not smoking, eating a healthy diet, limiting exposure to sunlight, and so forth. Should individuals who smoke or are obese or go to tanning salons pay a larger portion of the cost of treatment for any cancers they develop than individuals who do not smoke, who eat right and exercise, and who protect themselves against exposure to sunlight?
4. Should cancers that develop in people over 60 be treated as aggressively as those that develop in younger people? What about cancers that develop in people over 70? People over 80?
5. **CLINICAL CLICK QUESTION**
   Julio ran every evening after his work was done. This was a habit he picked up while in college as it seemed to help relax him. Lately though, Julio noticed that he was far more tired than usual during his runs, and often his knee would twinge in pain as he ran. He initially attributed his left knee pain to a breakdown in his running shoe. When getting new shoes did not relieve the pain, Julio went to his doctor. In taking a history of the pain, the doctor noted that Julio was experiencing pain in his knee during running for over a month. Recently it had escalated to the point where he was constantly aware of pain in his knee. Upon examination, the doctor could feel a small lump on the lateral aspect of the tibia. An x-ray was scheduled for the left tibia the following week. Unfortunately, before the week was out Julio stumbled and fell while running. Amazingly, with that small impact Julio's tibia fractured. What do you suppose the emergency room medical team found when they tried to set Julio's fractured tibia? What was causing his knee pain prior to the break? What diagnostic tools might have identified Julio's bone disease earlier? What treatment options does Julio have at this point? Visit http://www.medicinenet.com/bone_cancer/article.htm to verify your diagnosis, and suggest a suitable treatment.

What is happening in this picture?

Markings placed on this individual guide the technician in the correct placement of a therapeutic beam of radiation. The medical technician can guide both the position of the beam and the depth of its penetration. As the patient lies quietly, the technician will deliver a blast of energy to the cancerous tissues. The desired effect of this radioactive blast is to prevent the cells in its path from dividing.

Think Critically

1. How will this blast of energy affect the cells in its path?
2. What are the negative side effects of this treatment?
3. Why would this individual agree to the treatment, considering the potential side effects?
4. What other options might have been explored, and why do you suppose they were ruled out?

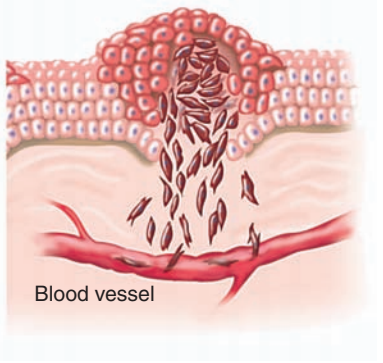
Self-Test

1. Which of the following is NOT a characteristic of cancer cells?
   a. unlimited replication potential
   b. no differentiation
   c. abnormal mitochondria
   d. deleted, duplicated, or otherwise mutated DNA

2. A malignant tumor may or may not be cancerous.
   a. True
   b. False

3. Cancer-causing genes that undergo mutations referred to as gain-of-function mutations are _____.
   a. p53 genes
   b. tumor-suppressor genes
   c. mutator genes
   d. proto-oncogenes

4. Identify the stage of carcinogenesis illustrated below:
   a. *in situ*
   b. spreading
   c. metastasis
   d. tumor death



5. Which of the following is NOT a category of cancer causes?
   a. heredity
   b. bacteria
   c. environment
   d. diet

6. BRCA1 and BRCA2 genes are both _____.
   a. involved in breast cancer
   b. tumor-suppressor genes
   c. carried in every cell of the body
   d. All of the above options are correct.

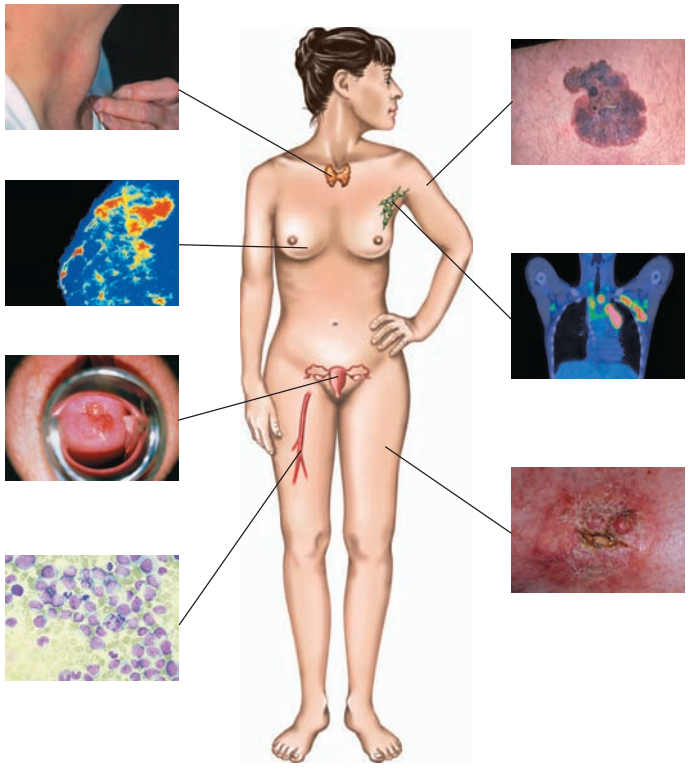
7. The two most prevalent forms of environmental carcinogens are _____.
   a. chemicals and viruses
   b. viruses and bacteria
   c. radiation and chemicals
   d. Only chemicals are environmental carcinogens.

8. Viruses are responsible for causing _____.
   a. lymphoma
   b. Kaposi's sarcoma
   c. cervical cancer
   d. All of the above options are correct.

9. Vitamin C aids in cancer prevention by _____.
   a. cleansing the colon
   b. removing free radicals
   c. attacking the supply of nutrients to a tumor
   d. reducing toxic buildup caused by shellfish consumption

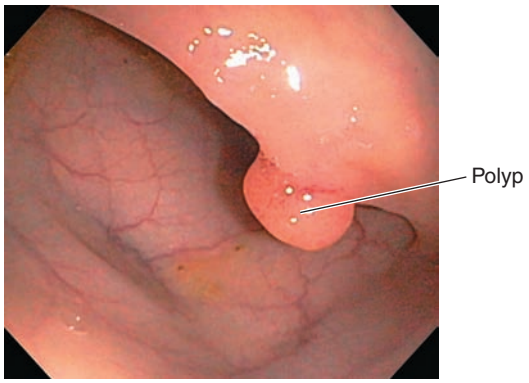
10. Leukemias are cancers of _____.
    a. epithelial tissue
    b. connective tissue
    c. nervous tissue
    d. muscular tissue

11. This illustration indicates all of the following except a(n) _____.
    a. sarcoma
    b. carcinoma
    c. adenoma
    d. blastoma



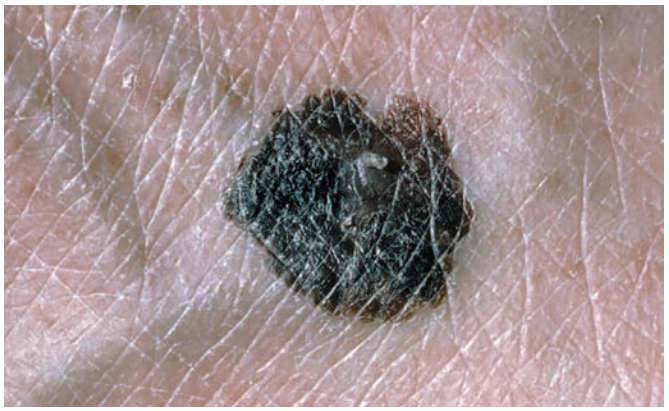
12. The procedure shown here is used to detect _____.

a. breast cancer
b. any sarcoma
c. colon cancer
d. skin cancer



13. The skin cancer identified in this photo is _____.

a. a basal cell carcinoma
b. a melanoma
c. a squamous cell carcinoma
d. This is not a cancerous tumor.



14. An MRI is most helpful in diagnosing _____.

a. cancers in protected areas, such as the brain
b. the cross-sectional appearance of a tumor
c. density differences within a tumor
d. tumors found within connective and muscular tissues

15. Adding compounds, such as interleukin-2, interferons, and tumor necrosis factor, to the body is an example of _____.

a. immunotherapy
b. chemotherapy
c. genetic therapy
d. anti-angiogenesis therapy

THE PLANNER

Review your Chapter Planner on the chapter opener and check off your completed work.

12 The Cardiovascular System

What sets Olympic and professional athletes apart from the rest of us? Many factors combine to produce high-caliber athletes, among them perseverance and dedication. Along with the proper attitude, being an elite athlete requires a physiology that can be transformed through training into one far more responsive to the sudden demands of Olympic and professional sports.

One key to this level of performance is the movement of blood, and therefore of oxygen and glucose, through the body. This is the job of the heart. An athletic heart is one that has been trained to beat more efficiently. Two advantageous changes occur in the athletic heart. The volume of blood the heart can hold increases, and the walls of the heart become stronger so fewer heartbeats are needed to pump the same volume of blood through the cardiovascular system. Called "athletic heart syndrome," this combination of features permits the cardiovascular system to respond more quickly to excess energy demands. Regular exercise will improve the functioning of anyone's heart, measurable by monitoring the pulse rate. If your pulse rate is lower than the national average of 70 to 75 beats per minute, then you are on your way to a healthier cardiovascular system.

In this chapter, we will introduce the structure and function of the heart as well as the rest of the cardiovascular system and then look at what can go awry with this essential delivery and trash removal system. The cardiovascular (CV) system is a triumph of sophisticated design, but cardiovascular problems are all too common.

CHAPTER OUTLINE

The Heart Ensures Continual, 24/7 Nutrient Delivery 310

- The Heart Is a Three-Layered, Four-Chambered, Two-Cycle Organ
- The Heartbeat Is Under Intrinsic and Extrinsic Controls
- The Electrocardiogram Records Electrical Activity

Blood Transport Involves Miles of Sophisticated Plumbing 318

- Each Type of Vessel Has a Specific Function

Different Circulatory Pathways Have Specific Purposes 321

- The Pulmonary Circuit Exchanges Carbon Dioxide for Oxygen in the Lungs
- The Systemic Circuit Delivers Oxygen to Tissues and Returns Carbon Dioxide

Cardiovascular Disorders Have Life-Threatening Consequences 322

- High Blood Pressure Stresses the Entire Body
- Artery Damage Is a Major Cause of Mortality and Disability
- Heart Attacks Have Causes and Consequences
- Congestive Heart Failure Is Due to a Weak Heart
- When Veins Become Visible They Function Less Effectively
- Even the Athletic Heart Can Fail

Blood Consists of Plasma and Formed Elements 327

- Plasma Is 46–63% of Total Blood Volume
- The Formed Elements of Blood Are Cells and Cell Fragments
- White Blood Cells Are Defensive Cells
- Red Blood Cells Carry Oxygen
- Red Blood Cell Surface Proteins Determine Blood Type
- Platelets Govern Blood Clotting
- Blood Can Suffer Many Disorders

CHAPTER PLANNER

- ❑ Study the picture and read the opening story.
- ❑ Scan the Learning Objectives in each section:
  p. 310 ❑ p. 318 ❑ p. 321 ❑ p. 322 ❑ p. 327 ❑
- ❑ Read the text and study all figures and visuals. Answer any questions.

Analyze key features

- ❑ Biological InSight, p. 312
- ❑ Process Diagram, p. 315 ❑ p. 316 ❑ p. 320 ❑ p. 336 ❑
- ❑ What a Scientist Sees, p. 325
- ❑ Ethics and Issues, p. 328
- ❑ I Wonder..., p. 333
- ❑ Health, Wellness, and Disease, p. 337
- ❑ Stop: Answer the Concept Checks before you go on:
  p. 318 ❑ p. 320 ❑ p. 322 ❑ p. 327 ❑ p. 338 ❑

End of chapter

- ❑ Review the Summary and Key Terms.
- ❑ Answer the Critical and Creative Thinking Questions.
- ❑ Answer What is happening in this picture?
- ❑ Answer the Self-Test Questions.

12.1 The Heart Ensures Continual, 24/7 Nutrient Delivery

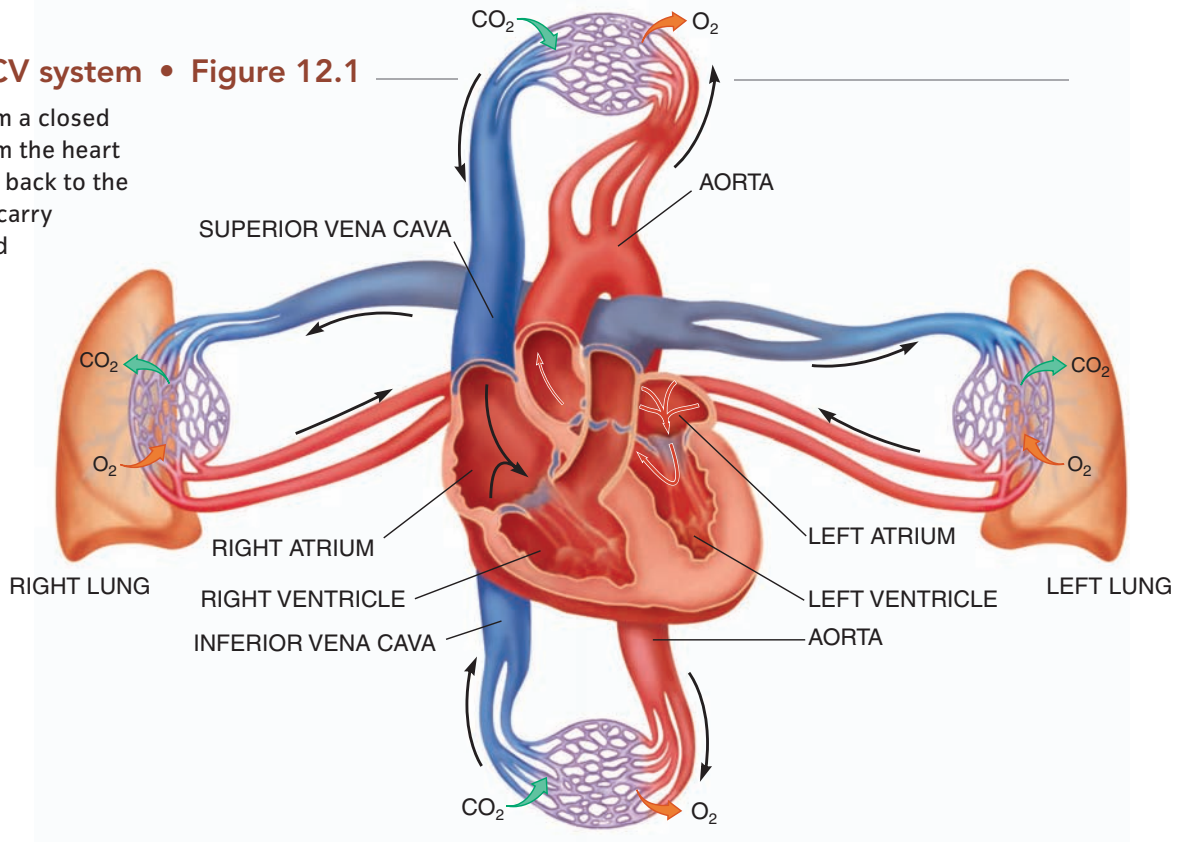
LEARNING OBJECTIVES

1. **Describe** the structure of the heart and blood flow through it.
2. **Define** extrinsic and intrinsic heart controls.
3. **Explore** the electrical signaling that produces contraction.
4. **Describe** how the tracings on an ECG reflect the heart's beat.

On the day Dr. Seuss's Grinch discovered the true meaning of Christmas, his heart grew three sizes. The Tin Man in the *Wizard of Oz* wanted a heart so he could have emotions. We've all heard the heart described as our emotional center, but physiologically speaking the heart is the center of the cardiovascular system. The heart is a pump that pushes blood through miles of blood vessels. The blood pressure generated by each heartbeat ensures that nutrients and oxygen reach every cell, directly or indirectly.

To understand the importance of the CV system, look at any large city. Vehicles transport food, goods, and raw materials into the city and deliver them to residents and institutions. After the goods are consumed, waste that is left over must be recycled, burned, reused, or shipped away. Any obstruction to this flow is likely to damage the city. Within days after trash collectors went on strike in the 1980s, garbage was piling up along the streets of New York City, blocking traffic, impeding business, and offending millions of noses. The city almost ground to a halt until a new contract was signed and trash removal resumed. Similarly, if the human body cannot move water, nutrients, and oxygen into the tissues and remove wastes from them, tissues will die, and the organism will die as well.

In delivering oxygen and removing carbon dioxide, the cardiovascular and respiratory systems work together. The **respiratory** system (Chapter 13) brings oxygen to the blood and removes carbon dioxide from it. The **cardiovascular** system transports that blood, carrying nutrients, wastes, and dissolved gases to and from the tissues. The cardiovascular system includes the **heart**, **blood vessels**, and **blood**. We will look first at the heart and the blood vessels, and then at the blood that flows through that closed circuit. See Figure 12.1.

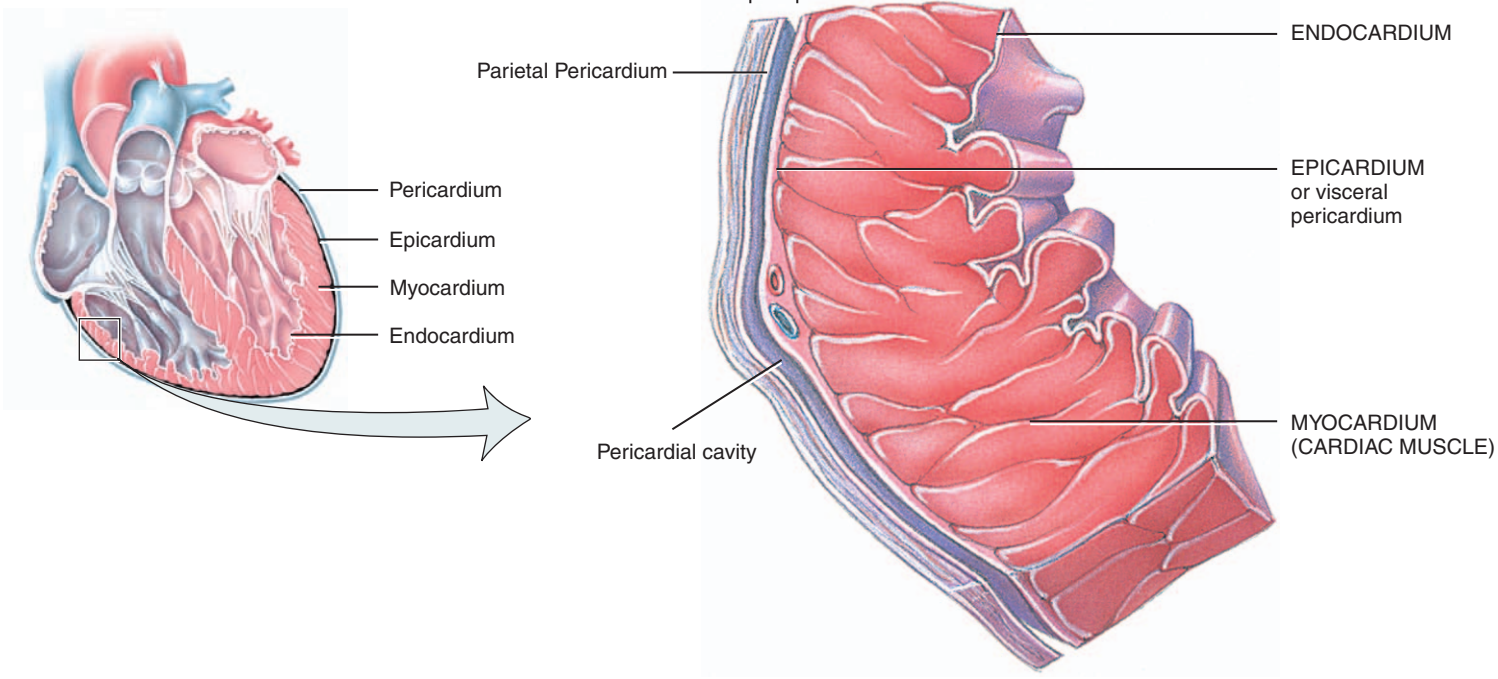


Basic schematic of the CV system • Figure 12.1

The heart and blood vessels form a closed circuit that transports blood from the heart to various parts of the body and back to the heart. The blue-colored vessels carry blood rich in carbon dioxide, and red vessels carry blood rich in oxygen.

Heart layers • Figure 12.2

The pericardium is composed of two layers. The parietal pericardium lines the walls of the sac where the heart is found. The visceral pericardium, or epicardium is attached directly to the myocardium. The space between these two is the pericardial cavity. It is filled with serous fluid.



Portion of pericardium and right ventricular heart wall showing the divisions of the pericardium and layers of the heart wall

The Heart Is a Three-Layered, Four-Chambered, Two-Cycle Organ

The heart resides in the center of the thoracic cavity, hanging by the great blood vessels that deliver and remove blood. The **pericardium** is a serous membrane, secreting a lubricating fluid that surrounds the heart and allows it to beat without causing damage to itself—beating causes the heart to jump around in the area between the lungs, the **mediastinum**.

mediastinum The central portion of the thoracic cavity between the lungs, containing the heart, major blood vessels, and lymphatics.

The heart walls have three layers, as shown in Figure 12.2: the epicardium, myocardium, and endocardium. The myocardium is the muscle of the heart, contracting to create heartbeats.

The heart itself is composed of four chambers: two **ventricles** and two **atria**. The atria are smaller, thin-walled chambers sitting atop the thick-walled, muscular ventricles. The atria receive blood from large veins and direct it into the ventricles, which expel the blood under great pressure toward the lungs or body.

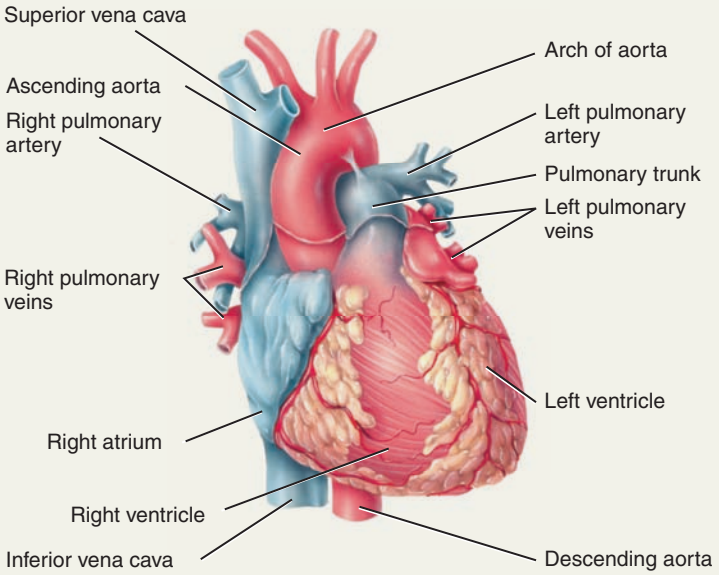
The adult heart is shown in Figure 12.3, on the next page. Note the thick ventricular walls, especially in the left ventricle. It is the left ventricle that must generate enough force to push blood throughout the body. The less muscular right ventricle pushes blood only to the nearby lungs. The walls of the atria are even less muscular, because these chambers are essentially holding tanks for blood after it returns from the body or lungs, rather than pumping chambers. Note also that the two sides of the heart are divided by a thick wall called the septum.

Biological InSight

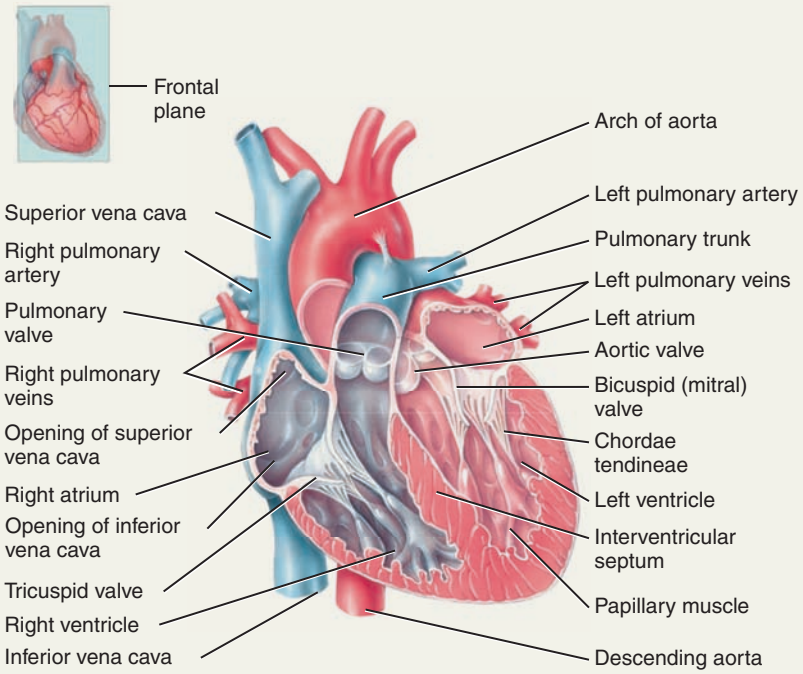
The adult heart • Figure 12.3

THE PLANNER

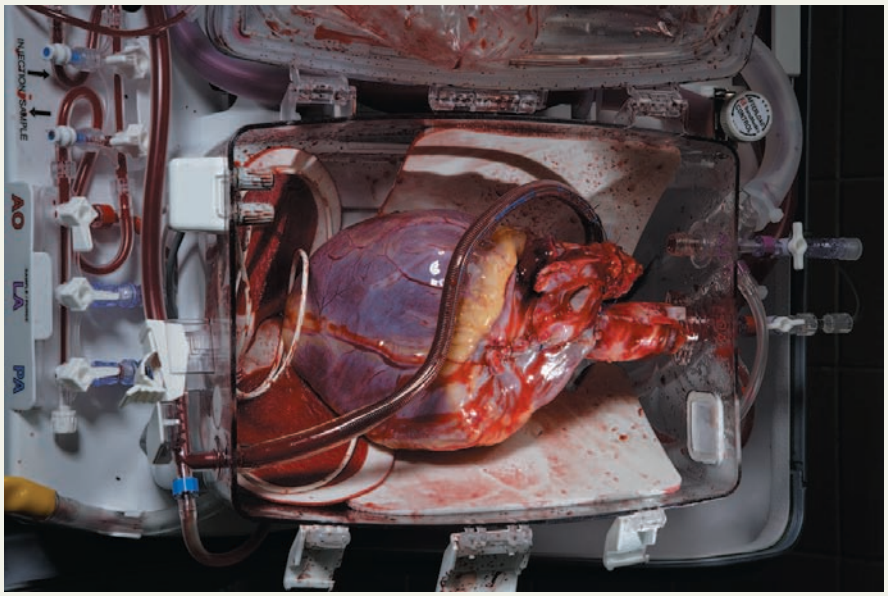
From the external view of the heart, it is obvious that the heart itself gets blood from separate right and left coronary arteries, not from the blood it pumps. Inside the heart, the four chambers are evident. The two ventricles are separated by a wall of cardiac muscle called the septum. Note the difference in thickness between the left and right ventricular walls. The right ventricle generates less force than the left.



a. Anterior external view showing surface features



b. Anterior view of the frontal section showing internal anatomy



Human heart for transplant, in transit between donor and recipient.

NATIONAL GEOGRAPHIC

Each heart chamber contains a valve. Each heart chamber contains one valve that opens to allow blood to pass and then closes when the chamber contracts to pump. Because these valves are found between the atria and the ventricles, they are called atrioventricular valves. The atrioventricular valves are the **tricuspid** valve in the right ventricle and the **bicuspid**, or **mitral** valve, in the left ventricle. Valves are composed of dense, irregular connective tissue and are held in place by the **chordae tendineae** (literally chords of tendons). These "heart strings" anchor the cusps of the valves to the **papillary muscles**. When we listen to a heart beat, even without a stethoscope, part of what we hear is the thrumming of the heartstrings as they are pulled tight and pressurized blood flows past them.

tricuspid The valve between the right atrium and right ventricle, composed of three points (cusps) of connective tissue.

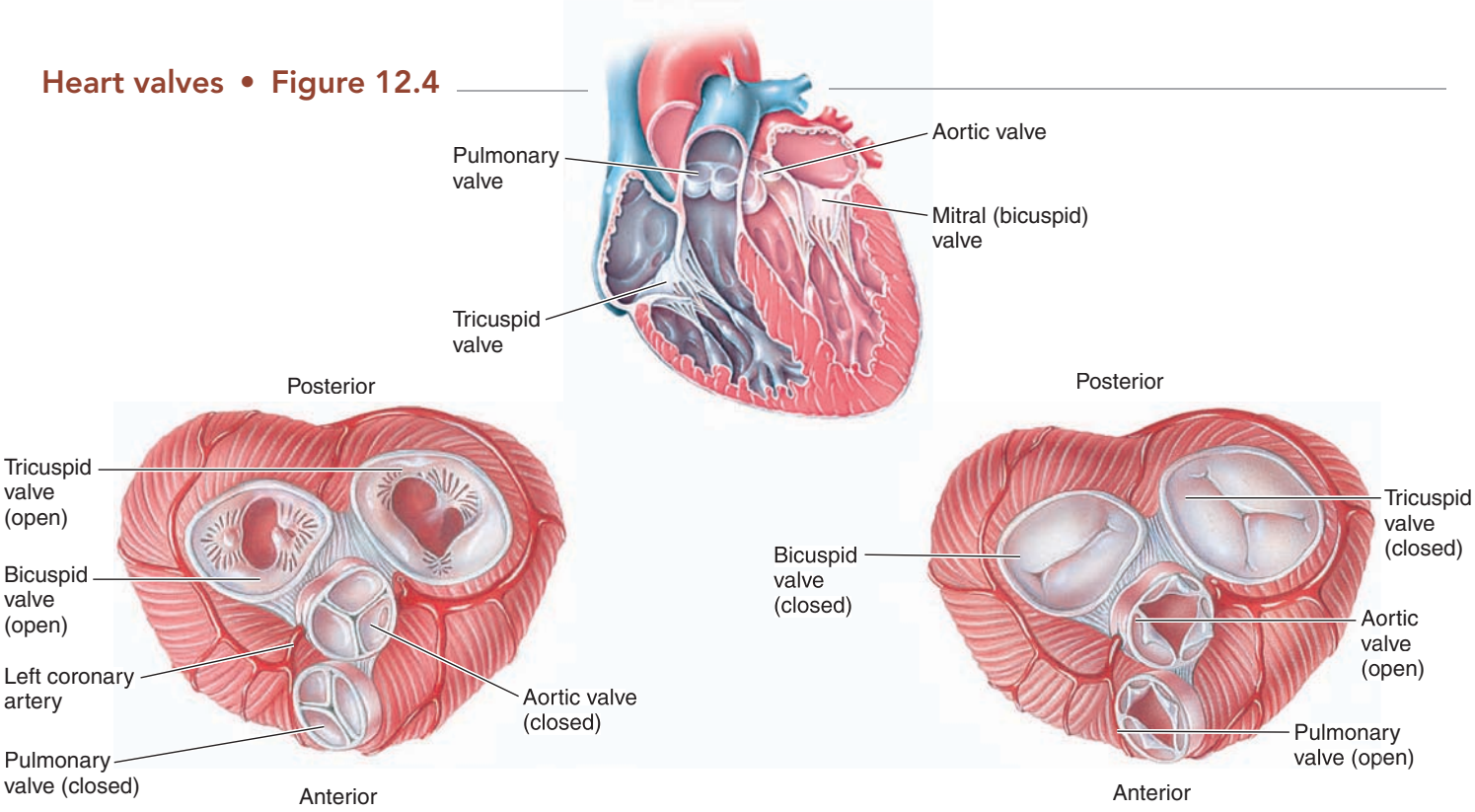
bicuspid The valve between the left atrium and left ventricle, composed of two opposing cusps or flaps of connective tissue.

Heart valves can flutter, hum, rasp, and tap. If the opposing surfaces of a valve fit poorly, blood can slip past, causing the valve to flutter. This fluttering creates a murmur (an audible change in heart sound) and can possibly lead to valve **prolapse**. The most leak-prone valve is the mitral valve in the left ventricle. When the mitral valve fits poorly, the condition is called mitral valve prolapse (MVP). MVP runs in families and affects more women than men. Although MVP saps heart efficiency, patients rarely report symptoms and usually require no medical treatment.

prolapse Movement of an organ from its original position in the body, usually because of gravity or pressure.

At the base of the great arteries leaving the heart are the **pulmonary** and **aortic valves**. These valves are shaped like three flexible bowls, anchored to the walls of the great vessel, as shown in Figure 12.4. When the heart pushes blood into the pulmonary or aortic artery, the bowls flatten against the artery walls so the blood can flow freely. When pressure drops inside the heart, blood in the arteries pushes back, ballooning the three bowls so they open and contact one another, closing the arterial opening leading back to the heart. Because these valves lack chordae tendineae, these valves make no humming sound when they close. Instead, they produce a tapping noise as they fill and knock against one another. This sharper noise can be heard as the second portion of the heartbeat.

Heart valves • Figure 12.4



a. Superior view with atria removed: pulmonary and aortic valves closed, bicuspid and tricuspid valves open

b. Superior view with atria removed: pulmonary and aortic valves open, bicuspid and tricuspid valves closed

Thinking about the heartbeat, we immediately imagine the characteristic "lubb-dupp" sound. This sound is generated by the valves, and it can have clinical significance. Normal heart sounds are called S1 ("lubb") and S2 ("dupp"). S1 is a loud, resonating sound caused by blood pressure against the atrioventricular valves. This pressure closes the bicuspid and tricuspid valves, pulling the chordae tendineae and the entire supporting framework of cardiac muscle. The second sound forms when the ventricles relax and blood in the pulmonary artery and the aorta flows back toward the ventricles. The arterial valves catch the backflow and snap against one another—"dupp." If the two ventricles are slightly out of sequence, so that one closes first, S2 may "stutter" or "split." An occasional split S2 is normal, but a constant split may indicate **hypertrophy** of one ventricle, a serious cardiac disorder. Listening to these heart sounds, or any internal body sounds for that matter, is termed **auscultation**.

hypertrophy Enlargement of an organ due to enlarged cells rather than an increasing number of cells.

The heart can murmur as well. A heart "murmur" can indicate valve malfunction. This whooshing, blowing, or rasping noise occurs when blood passes the valves in a turbulent flow. Murmurs may signal serious valve trouble, but not all murmurs are cause for alarm. Children often develop a murmur as they grow, because the cardiac muscle grows much faster than the valves, which are made of connective tissue. For a while, the valves are simply too small for the heart! Many women develop a murmur during pregnancy as a result of the dramatic increase in blood volume. Pumping the extra volume exaggerates any small murmurs that are present.

Blood flows twice through the heart. Blood enters the heart twice during one complete circuit of the cardiovascular system—once through the right side and then again through the left. Blood enters the right atrium from the **superior** and **inferior vena cavae** and the **cardiac sinus**, and then drops through the tricuspid atrioventricular valve into the right ventricle, which pumps blood to the lungs.

cardiac sinus Large vein on the dorsal surface of the right atrium that collects blood from the cardiac veins and returns it to the chambers of the heart.

Blood that returns from the lungs enters the left atrium and drops through the mitral valve into the left ventricle, which pumps the blood throughout the body (with the exception of the respiratory membranes of the lungs). This cyclic movement of blood through the heart and body is propelled by the cardiac cycle of the heart. The Figure 12.5 insert shows this.

At the beginning of the cardiac cycle, the heart is in **diastole**. See **Figure 12.5**. The ventricles have relaxed after their recent contraction, and their volume has increased. This increase in volume quickly decreases the pressure in the ventricles below that of the atria, drawing in blood through the atrioventricular (AV) valves. The majority of ventricular filling occurs as these AV valves open. Then the two atria undergo **systole** and force the remaining atrial blood into the ventricles. This step takes approximately 0.15 second.

diastole Relaxation of the heart.

systole Contraction of the heart.

After atrial systole, the ventricles contract, taking another 0.30 second. The rapid pressure increase inside the ventricles forces the atrioventricular valves closed, and the semilunar valves open. The blood trapped in the ventricles cannot escape back to the atria through the atrioventricular valves, so it is forced through the semilunar valves, into the great arteries. Blood leaves the right side of the heart via the pulmonary valve and enters the **pulmonary trunk**, which takes it to the respiratory membranes of the lungs. The blood exiting the left ventricle passes through the aortic valve and reaches the organs of the body.

As the ventricles contract, the atria relax. After a brief ventricular contraction, the entire heart relaxes. Most of the cardiac cycle (an average of 0.40 second) is spent in diastole.

The volume of blood doesn't usually change, but its pressure does. The heartbeat propels blood through the closed cardiovascular system. As the ventricles undergo systole, they exert pressure on the blood in the entire cardiovascular system. The force created by the left ventricle generates the pulse we can feel and the blood pressure that is measured at the doctor's office. You may be able to recite your blood pressure, which is presented in standard form as systolic pressure over diastolic pressure, such as 110/60 or 193/85.

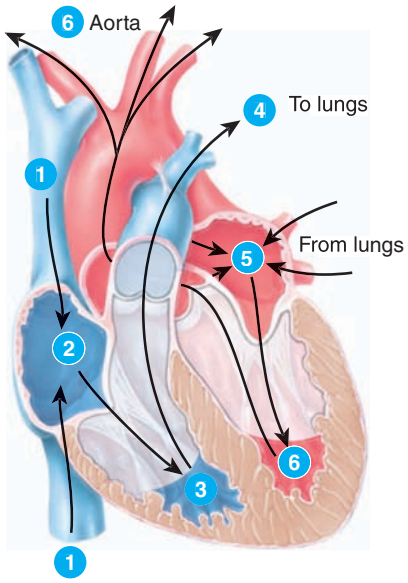
These numbers have physiological meaning. Systolic pressure measures the force of left ventricle contraction, which pushes blood through the circulatory system. This number is low in children and creeps up with age, as the blood vessels become less elastic. Diastolic pressure is the force your blood exerts on the walls of your closed circulatory system while the heart is in complete diastole (relaxation). Contrary to popu-

The cardiac cycle • Figure 12.5

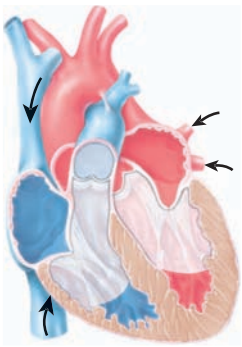
THE PLANNER

Blood flows through the heart from the right side to the lungs, then back to the left side, and on to the tissues of the body. The cardiac cycle is the sequence of diastole and systole the heart undergoes to accomplish this blood flow.

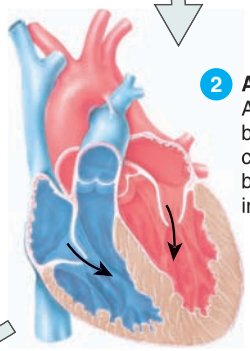
WILEY PLUS Interactivity



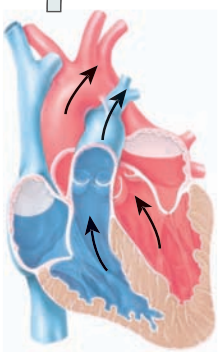
1. vena cava
2. right atrium
3. right ventricle
4. on to lungs
5. back to the left atrium
6. left ventricle, and then out to the body through the aorta.



1 Diastole (relaxation period)
At the beginning of the cycle, the heart is completely relaxed, with blood entering both the left and right atria.



2 Atrial systole
As the heartbeat begins, the atria contract. This forces blood from the atria into the ventricles.



3 Ventricular systole
Soon after atrial systole, ventricular systole occurs. The atria relax during ventricular systole. The ventricles remain contracted for a measurable time, and then the entire heart returns to diastole.

lar belief, the diastolic number cannot be zero unless all the blood has been drained from the organism. High blood pressure is loosely defined as a blood pressure reading of 140/90 or above (discussed in Section 12.4, *Cardiovascular Disorders Have Life-Threatening Consequences*, later in this chapter).

The Heartbeat Is Under Intrinsic and Extrinsic Controls

Your heart began beating during your third week of development, and it must continue beating to supply your body's oxygen and nutrient demands until the last minutes of your life. The rate of a heartbeat is under two types of control: **Intrinsic controls** establish the usual, day-in, day-out pace of heartbeats; **extrinsic controls** modulate the baseline rate to meet the body's immediate demands.

Intrinsic controls create a synchronized contraction. Unlike other muscle cells, cardiac muscle cells undergo rhythmic contractions without receiving nerve impulses. Recall that the trigger for skeletal muscle contraction is the calcium ion. Cardiac muscle cells are constantly leaking this important ion, and when the intercellular calcium concentration reaches threshold, the cell spontaneously contracts. (See Figure 12.6a.) When two or more cardiac muscle cells touch one another, they begin to beat in unison, following the pace of the faster cell.

A group of cells in the upper wall of the right atrium has the fastest intrinsic beat, and it serves as the heart's pacemaker. Because these pacemaker cells are near the entrance of the coronary sinus, they are called the **SA** (sinoatrial) **node**. When the SA node initiates the heartbeat, the signal to contract passes in wave-like fashion

from cell to cell through the right and then the left atrium, causing both to contract. According to the National Institutes of Health, the average adult intrinsic heartbeat is approximately 80 bpm. However, it can range from 60 to 100 bpm in healthy adults.

At the base of the left atrium, near the ventricle, lies a group of cells called the **AV node**. AV stands for atrioventricular, reflecting the placement of this node. These cells are a relay station that delays the contraction impulse before sending it on. (Like the cells of the SA node, the AV node cells cannot be distinguished visually.) The delay allows the atria to complete their contraction before the ventricles are stimulated to begin contracting. After the delay, the impulse passes through a series of conductive tissues before reaching the cells of the ventricles.

From their relative sizes, it's obvious that ventricles have far more cells than do atria. Although the impulse to contract could spread from cell to cell in the ventricles just as in the atria, the contraction would be ineffective because closer cells would have finished contracting before the contraction impulse reached more distant cells. Instead of producing the forceful contraction needed to build up pressure and open the semilunar valves, blood would just slosh around in the ventricle. If you try to pop a water balloon by grabbing the top, the middle, and bottom in order, the water will simply move away from your hands without breaking the balloon. However, if you can grab the balloon everywhere at once, the dramatic rise in internal pressure will pop it.

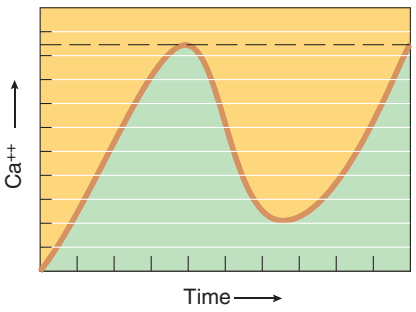
To obtain simultaneous contraction, the ventricles require a conduction system for the contraction impulse, as shown in Figure 12.6. This system starts at the AV node and goes to the **AV bundle** (or **bundle of His**) at the center of the heart, near the septum. Here the system splits into the **left** and **right bundle branches**, which

PROCESS DIAGRAM

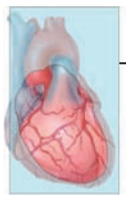
Conduction system of the heart • Figure 12.6

THE PLANNER

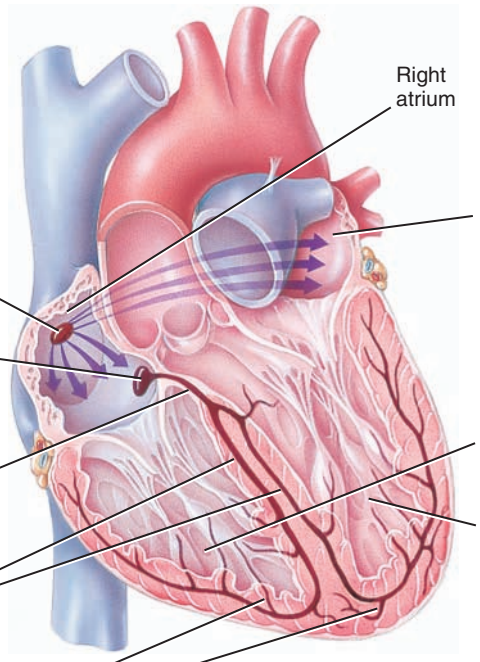
Intracellular calcium levels determine when a heart cell contracts. When the calcium level reaches threshold, the cell contracts, and calcium levels drop. The calcium level immediately begins to build up again, leading to the next contraction.



WILEY PLUS Interactivity



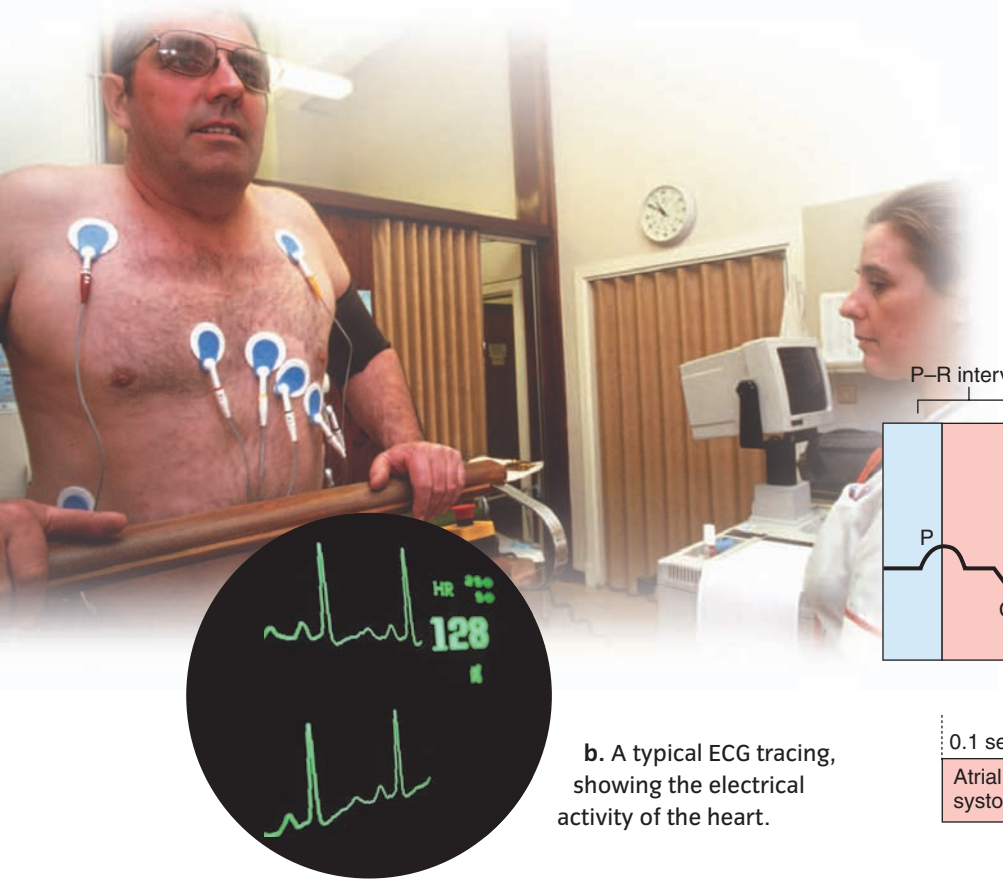
Frontal plane



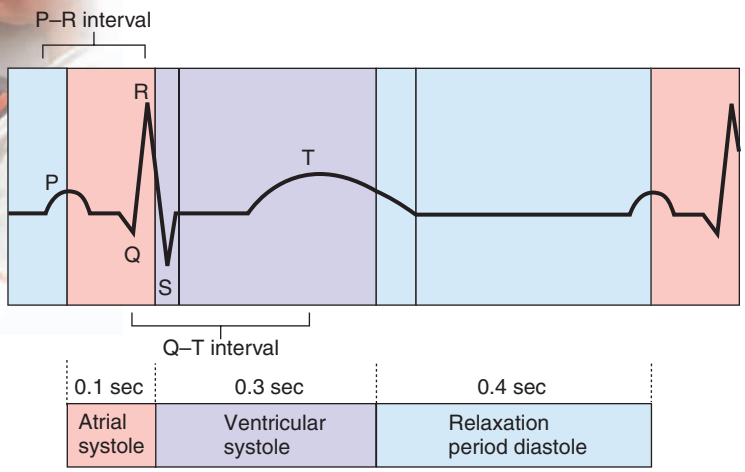
Anterior view of frontal section

1. SINOATRIAL (SA) NODE
The contraction impulse begins in the SA node.
2. ATRIOVENTRICULAR (AV) NODE
The contraction passes in a wave-like fashion through the atria and is collected at the AV node.
3. ATRIOVENTRICULAR (AV) BUNDLE
From the AV node, the impulse is sent down the AV bundle.
4. RIGHT AND LEFT BUNDLE BRANCHES
The impulse is then passed to the left and right bundle branches.
5. PURKINJE FIBERS
Finally the impuse passes through the Purkinje fibers, and then on into the cells of the ventricles.

The ECG is a powerful diagnostic tool • Figure 12.7



a. This man is hooked up to an ECG machine. The electrical changes associated with cardiac systole and diastole can be picked up on the surface of the body with electrodes attached to the skin. A conductive gel between the electrode and the skin enhances sensitivity. The resulting tracing is used to diagnose cardiac function.



b. A typical ECG tracing, showing the electrical activity of the heart.

carry the impulse to the apex of the heart and then up the outer walls. From the bundle branches, the impulse travels on smaller **Purkinje fibers**, which end at clusters of ventricular cells. Using this system, all ventricular cardiac muscle cells contacted by Purkinje fibers get the impulse simultaneously, resulting in synchronous contraction of the entire ventricle.

Purkinje fibers
Conduction myofibers that reach individual cells of the ventricles.

Extrinsic controls can override the intrinsic controls. The SA node and the conduction system govern the baseline, or resting, heart rate. However, if the body needs more blood than the resting heart rate can deliver, several **extrinsic heart rate controls** may enter the picture. One extrinsic control resides in the cardiac control center in the medulla oblongata. This center can override the intrinsic heartbeat, increasing or decreasing the rate as necessary. When the sympathetic division of the autonomic nervous system is active, heart rate increases significantly. Similarly, heart rate immediately rises in cardiac cells that are exposed to norepinephrine, the sympathetic division neurotransmitter.

The heart itself can also affect contraction rate and strength. **Starling's law** states that when the ventricles are stretched by increased blood volume, they recoil with matching force. Thus increased blood flow to the heart, which occurs when we start hard physical work or exercise, causes the heart to respond with more forceful pumping—just what we need to move oxygenated blood to the active muscles.

The Electrocardiogram Records Electrical Activity

Regardless of what is controlling the heart rate, the cardiac muscle cells generate a pattern of electrical signals as they go through the cardiac cycle. The cells of the myocardium depolarize immediately before they contract and repolarize as they relax. Because so many cells are involved in this cycle, the electrical signals are strong enough to be detected on the skin, where they can be recorded on an **electrocardiogram**, or ECG, as shown in Figure 12.7.

electrocardiogram
A graphic representation of the electrical conditions during a heartbeat.

The ECG tracing has a defined series of peaks and valleys. As the SA node fires, the atrial cells depolarize, causing a hill-shaped upward deflection called the **P wave**. Within 100 milliseconds, atrial systole follows. The ECG tracing briefly flattens, then starts a large upward deflection. This **QRS complex** is created by the simultaneous depolarization of the many ventricular cells. As the ventricles briefly remain in systole, the ECG is momentarily flat. As the ventricles relax, the cells repolarize, creating the deflection called the **T wave**, which marks the return of cardiac diastole.

These deflections can help clinicians evaluate cardiac function. During the **P–R interval** (from atrial depolarization to ventricular depolarization), the contraction impulse is transmitted from the SA node, through the atria, to the AV node, and finally through the conduction system. An interval longer than 0.2 second may indicate damage to the conduction system or the AV node. A long **Q–T interval** (the total time of ventricular contraction and relaxation) may indicate **congenital** heart defects, conduction problems, coronary **ischemia**, or even cardiac tissue damage from a previous heart attack. If the problems seen in the ECG are severe, the heart muscle may stop functioning properly or may be too weak to be effective.

congenital Present at birth.

ischemia Lack of oxygen to a tissue because of constriction or blockage of the blood vessels.

CONCEPT CHECK

STOP

1. **What** structures will a blood cell pass through as it moves through the heart from the vena cava to the aortic valve?
2. **What** are extrinsic and intrinsic heart controls?
3. **What** is the electrical pathway through the heart, beginning at the SA node and ending with the conduction systems that cause ventricular systole?
4. **What** does the P wave of an ECG indicate? **What** is the heart doing when the QRS complex appears on the ECG? **What** is the correct term for the heart as the ECG is drawing the S-T interval: systole or diastole?

12.2 Blood Transport Involves Miles of Sophisticated Plumbing

LEARNING OBJECTIVES

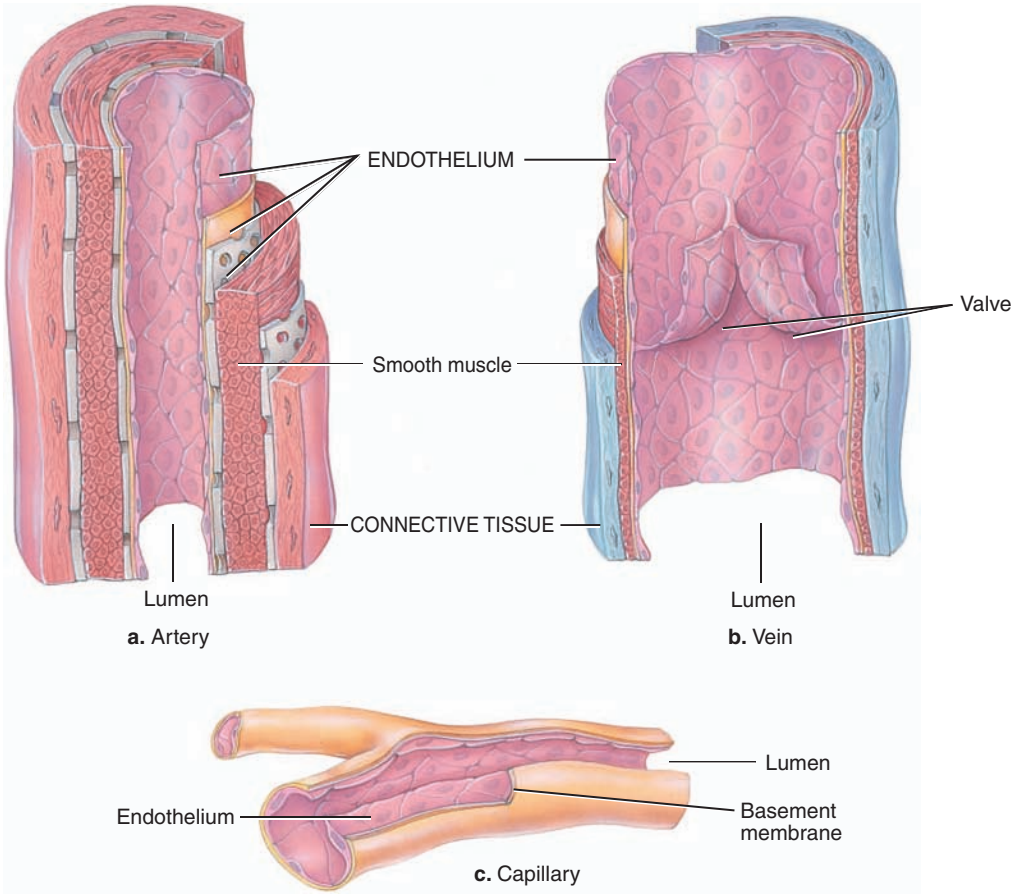
1. **Compare** the structure and function of the three types of blood vessels.
2. **Discuss** the function of capillary beds and venous valves.

The cardiovascular system has three categories of vessels that are strung together in a large web that begins at the heart, reaches the tissues, and returns to the heart. The vessels in this continuous circuit are the **arteries**, **capillaries**, and **veins**, and their detailed structures are shown in **Figure 12.8**. Each type of vessel has a different function, and therefore different forms. Walls of both arteries and veins have three layers:

- Endothelium, the inner layer
- Smooth muscle and elastic tissue in the middle layer
- Connective tissue making up the outside layer

Artery, vein, and capillary structure • Figure 12.8

Note that the artery is the thickest of the vessels. Arteries take blood from the heart to the tissues of the body and are subjected to the largest pressures. They have a layer of resilient muscle in their walls that allows for the bouncing pulse we can feel through the skin. Capillaries are extremely thin-walled, usually only one cell thick. They are the diffusion vessels of this system. Veins are thinner than arteries but have more substance than the capillaries. Valves prevent backflow of blood in these weak-walled vessels.



The arteries have thicker smooth muscle and connective tissue layers than veins, to handle the higher pressure the arteries are under. Venous walls are much thinner than arterial walls.

Each Type of Vessel Has a Specific Function

Arteries carry blood away from the heart. Arteries are blood vessels on the output (ventricular) side of the heart. Arteries closest to the heart have large diameters and thick walls because the heart's pumping causes them to stretch and recoil with each beat. Farther from the heart, diameter and wall thickness both decrease, because this distance reduces the fluid pressure from the heart. As the vessels get smaller, the ratio of the inner surface of their lumen to the volume that lumen holds goes from a small surface-to-volume ratio to a large surface-to-volume ratio. This directly affects blood flow, becauce there is more surface area to create friction and drag in smaller, more numerous vessels. **Arterioles** are small vessels that branch from larger arteries and are structurally similar. In the arterioles, the total cross-sectional area of the blood vessels increases, even though each vessel is smaller in diameter. This larger cross section causes the blood to slow. The smaller **lumen** exposes the blood to more surface area, which creates friction, further slowing the flow.

lumen The inner, hollow portion of a tubular structure; the center of the blood vessel.

Capillaries are vital units of exchange. Arterioles lead to **capillaries**, the smallest blood vessels. The wall of a capillary is one cell layer thick, and the lumen is barely big enough for one blood cell. Capillaries are exchange vessels that reach to almost every cell, and they are the only vessels that permit the vital exchange of gases, nutrients, and waste across the blood vessel wall. The slow blood flow and high cross-sectional area provide enough time and surface area for exchange to occur. Capillaries form large

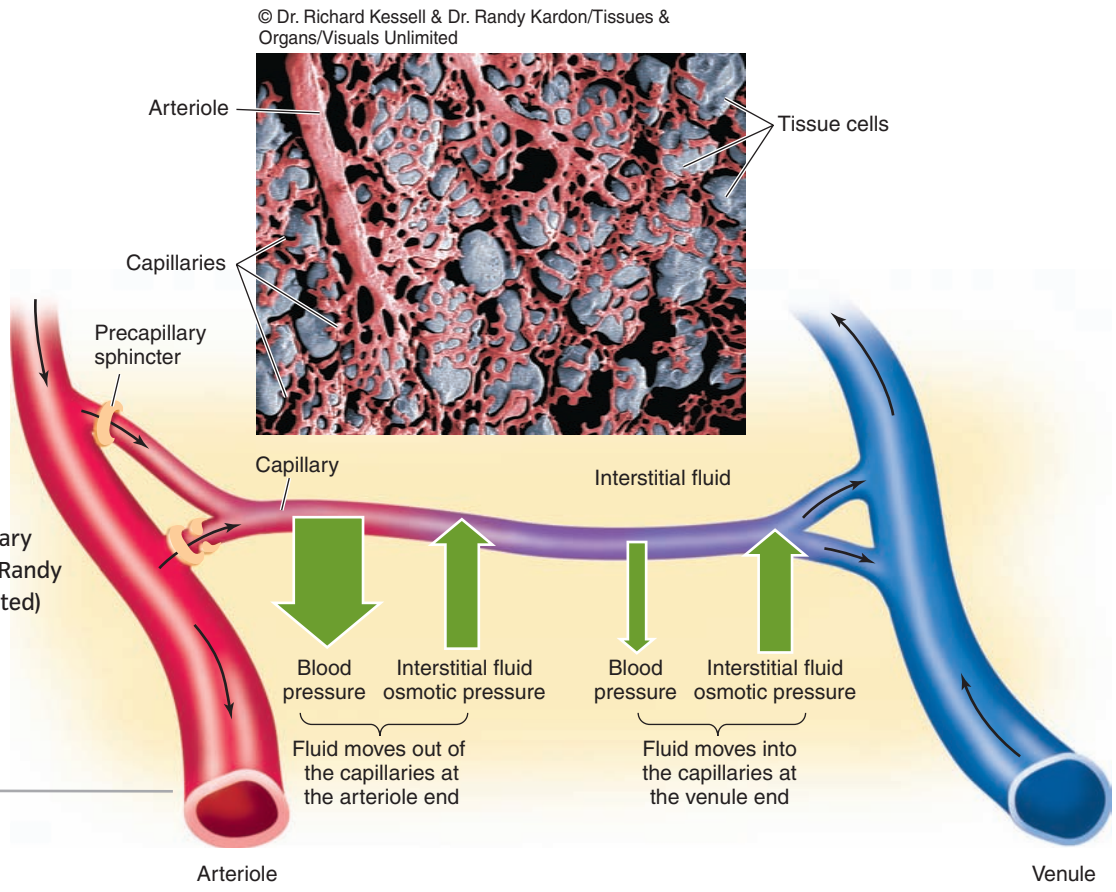
PROCESS DIAGRAM

Capillary bed and exchange flow • Figure 12.9

THE PLANNER

As blood flows through the capillaries, it slows to allow exchange of fluids, minerals, nutrients, and waste between the blood and the tissue fluid. This flow is directed by osmosis. Proteins in the blood maintain the blood's osmotic pressure, keeping water inside the capillaries as it passes through the tissues. Water in the tissues balances this osmotic pressure, preventing mass movement of water into or out of the tissues. At the arteriole end of the capillary, osmotic pressure is higher in the capillaries, and water with dissolved minerals moves into the tissues. This is reversed at the venous end of the capillary bed. (*Source*: ©Dr. Richard Kessel & Dr. Randy Kardon/Tissues & Organs/Visuals Unlimited)

WILEY PLUS Interactivity



capillary bed Interwoven mat of capillaries threading through a tissue.

capillary beds within the tissues, where blood flow is regulated by **precapillary sphincters**. These small, ring-like muscles can close or open parts of a capillary bed, depending on the oxygen and nutrient demands of the tissue. See **Figure 12.9**.

Veins bring blood back to the heart. Blood leaving capillaries collects in larger vessels called **venules** and veins heading back toward the heart. At this point, circulation resembles the flow of water from rivulets into creeks, then into rivers, and eventually to the sea. As the veins get bigger, the walls thicken slightly. Because the veins are beyond the capillaries, the heart's pumping cannot put much pressure on venous blood. Therefore, the veins are not as thick as arterial walls. The blood in the veins is moving with barely any pressure, so the veins do not need to be terribly strong.

venules Small veins that drain blood from capillaries to larger veins.

Despite the low pressure, the blood continues to flow toward the heart. Part of the reason is fluid dynamics: Fluids flow easily from a smaller vessel to a larger one, where there is less friction from the vessel walls. Returning the blood from the legs to the heart poses a special challenge because the flow must counteract gravity, with almost no help from the heart. Blood does not pool or flow backward in the legs, because a series of valves in the large veins prevent reverse flow. Also, the contraction of skeletal muscle squeezes the veins and creates a pumping action, pushing blood up toward the heart. Exercise is often prescribed to move blood and prevent **edema** of the lower extremities.

edema Abnormal swelling in tissues.

CONCEPT CHECK

STOP

1. **What** the three types of cardiovascular vessels, and **what** are their structure and function?
2. **What** is the function of venous valves? Capillary beds?

12.3 Different Circulatory Pathways Have Specific Purposes

LEARNING OBJECTIVES

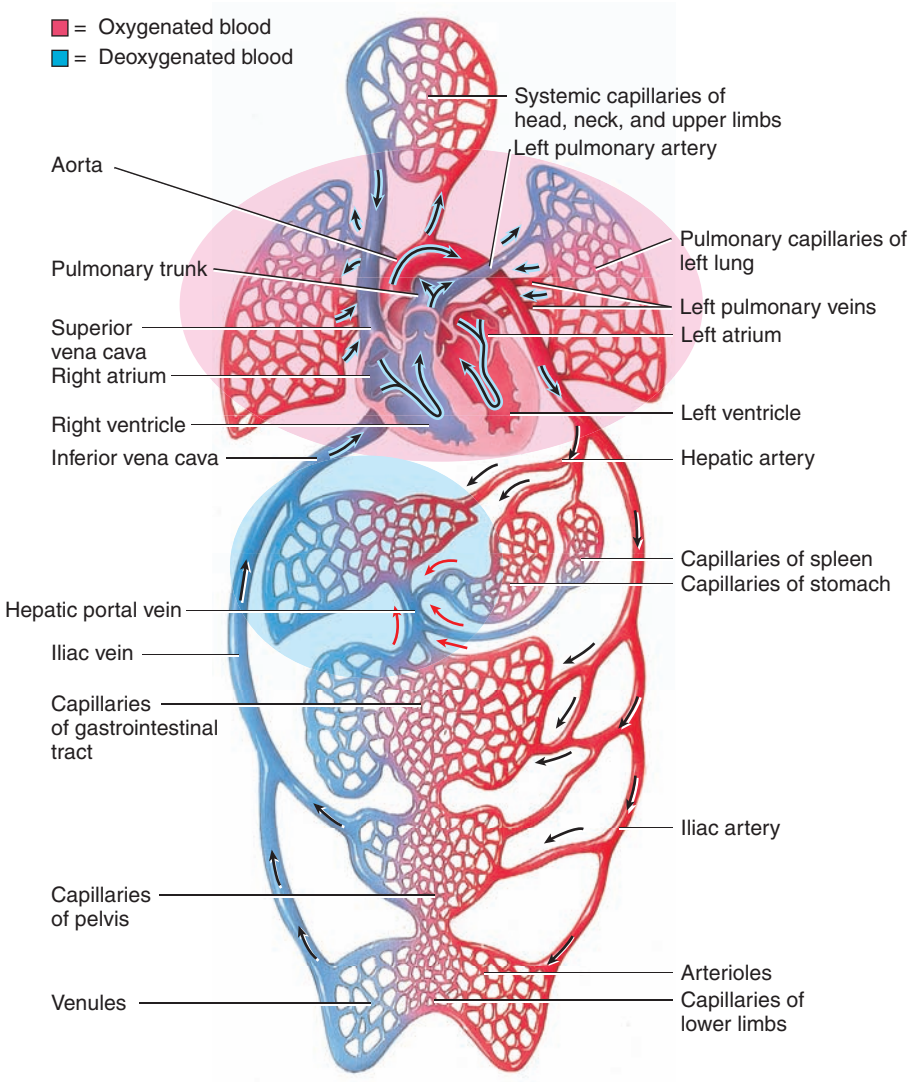
1. **Define** a closed circuit.
2. **Compare** the function and flow of the systemic, pulmonary, and hepatic portal pathways in humans.

Blood can take one of two pathways from the heart: the **pulmonary circuit** toward the lungs or the **systemic circuit** toward the tissues. The purpose of the pulmonary circuit is to exchange carbon dioxide in the blood for oxygen from the environment. The systemic circuit brings this oxygen (and nutrients) to the tissues and then removes carbon dioxide from them.

The Pulmonary Circuit Exchanges Carbon Dioxide for Oxygen in the Lungs

The **pulmonary circuit** extends from the right side of the heart to the capillary beds of the lungs and on to the left atrium, as shown in Figure 12.10. Blood entering the right atrium is low in oxygen, having just returned from the body. This deoxygenated, carbon dioxide–rich blood drops to the right ventricle and is propelled to the respiratory membrane of the lungs, where it picks up oxygen, releases carbon dioxide, and returns to the left atrium.

Pulmonary and systemic circulatory routes • Figure 12.10



The two main circulatory routes in the body are seen here. The pulmonary circulatory route takes blood from the heart to the respiratory surface of the lungs and back to the heart (short black arrows). The much more complicated systemic circuit delivers blood to the other organs and then back to the heart (longer black arrows). The red arrows represent the hepatic portal circulation.

The Systemic Circuit Delivers Oxygen to Tissues and Returns Carbon Dioxide

The **systemic circuit** begins when oxygen-rich blood enters the left atrium. This oxygen-rich blood then enters the left ventricle and, during ventricular systole, is pumped through the aortic arch to the body. After passing through the capillaries, venous blood returns to the superior and inferior vena cavae. These large veins drain into the right atrium, where blood reenters the pulmonary circuit. The systemic circuit includes most blood vessels in the body.

The first branches from the aortic arch are the **coronary arteries**, which deliver oxygen-rich blood to the cardiac muscle. Although the left side of the heart is full of oxygen-rich blood, that blood and its oxygen are not available to the heart tissue because the inner lining of the heart, the **endocardium**, is not a diffusion membrane. Therefore, cardiac tissue must obtain oxygen through a capillary bed, just like every other tissue. The coronary arteries are narrow and prone to clogging. If they are blocked, less oxygen-rich blood can be delivered to the heart, causing a heart attack. Heart attacks are discussed later in this chapter.

Although blood usually flows from arteries to capillaries to veins, this pattern is modified in a few places. In **portal systems**, blood flows from arteries to capillaries to veins, as usual. The veins, however, break up into another set of capillary beds before the blood returns to the heart. This allows the blood to slow in the organ before being pushed back to the heart.

Before blood enters the liver, it absorbs nutrients in capillary beds in the small intestine. This blood collects in the hepatic portal vein, which drains from the small intestine to the liver, and then passes through another capillary bed. The blood flow slows in the capillary bed of the liver so *hepatocytes* (liver cells) can remove detrimental ions and compounds that were picked up by the digestive tract. The cleansed blood collects in the hepatic vein and drains to the inferior vena cava.

CONCEPT CHECK STOP

1. **What** is a closed circulatory circuit?
2. **How** does the pulmonary circuit differ from the systemic circuit and the hepatic portal system?

12.4 Cardiovascular Disorders Have Life-Threatening Consequences

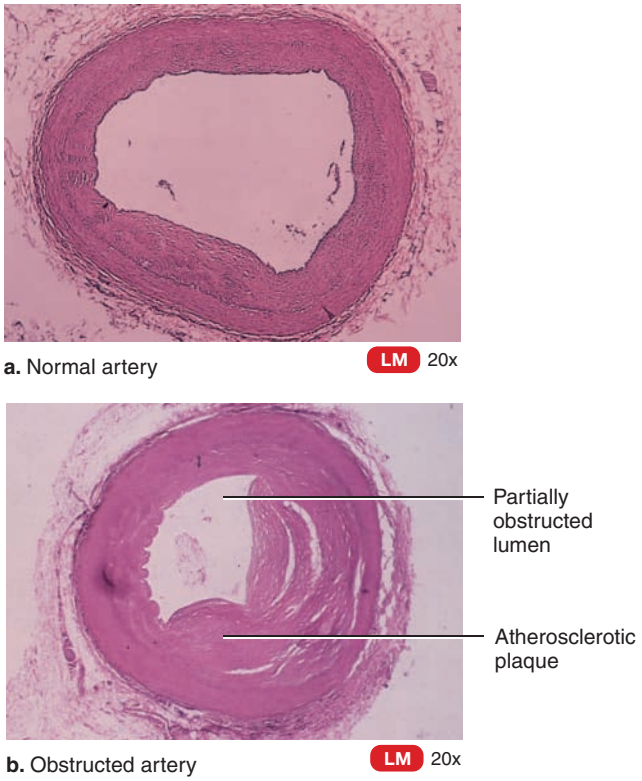
LEARNING OBJECTIVES

1. **Discuss** the dangers of high blood pressure and artery damage.
2. **Probe** the risk factors for heart attack.
3. **Explain** the ramifications of weak venous walls.
4. **Explore** the role of lifestyle in cardiovascular disease.

Many cultures equate great emotional pain with a "broken heart," but in reality, love gone awry does not interfere with cardiac function. However, **cardiovascular disease** (CVD) does, and in fact is a leading cause of death in Western countries. CVD takes many forms, each with its own symptoms and treatments.

The most common cardiovascular diseases include hypertension, atherosclerosis, heart attack, heart failure, embolism, stroke, and varicose veins. You probably know someone who has suffered from one of these conditions. The risk factors for cardiovascular disease can be genetic or environmental. Genetic risk factors include family history, gender, and ethnic background. A family history of heart attack prior to age 55 indicates a genetic predisposition to heart disease. Males suffer from CVD more frequently than females, although this gap is closing. The reasons for this change could include the advancement of women into the higher-stress jobs once dominated by men, women's longer life spans, and the postmenopausal reduction in estrogen levels. The incidence of CVD is higher in African Americans than in Americans of European descent, indicating a genetic predisposition.

Plaque formation • Figure 12.11



a. Normal artery — LM 20x

b. Obstructed artery — LM 20x

Even if you have genetic risk factors, all is not lost. Many risk factors, such as smoking, overeating, and spending too much time on the sofa rather than exercising, are fairly easy to control. Monitoring your diet and getting a modicum of exercise will decrease your chance of CVD. Some studies indicate that 40 minutes a day of low-impact exercise reduces the chance of heart disease by one-third. The exercise need not be terribly strenuous—gardening, yoga, or ballroom dancing can all improve cardiovascular performance. In many cases, preventing or controlling CVD is not difficult; it just requires some understanding and dedication.

High Blood Pressure Stresses the Entire Body

One of the most prevalent CVDs is **hypertension**, or high blood pressure. Hypertension is often called the "silent killer," because it may produce no symptoms before disaster strikes. Hypertension is diagnosed when systolic blood pressure is above 140 mmHG, or diastolic pressure is above 90 mmHG. A high diastolic number indicates a decline in blood-vessel elasticity that increases the chance that the force of systolic contraction will exceed the capacity of the circulatory system. Although hypertension is harmful to many organs, the key risk is stroke. Dietary restrictions, moderate exercise, reduction of smoking and drinking, and medications can all control hypertension.

Recent research is discovering a genetic link to some forms of high blood pressure. In particular, two genes are involved in the conversion and activation of the protein angiotensinogen. This protein constricts the blood vessels. If this pathway is hyperactive, constricted vessels will result, increasing blood pressure.

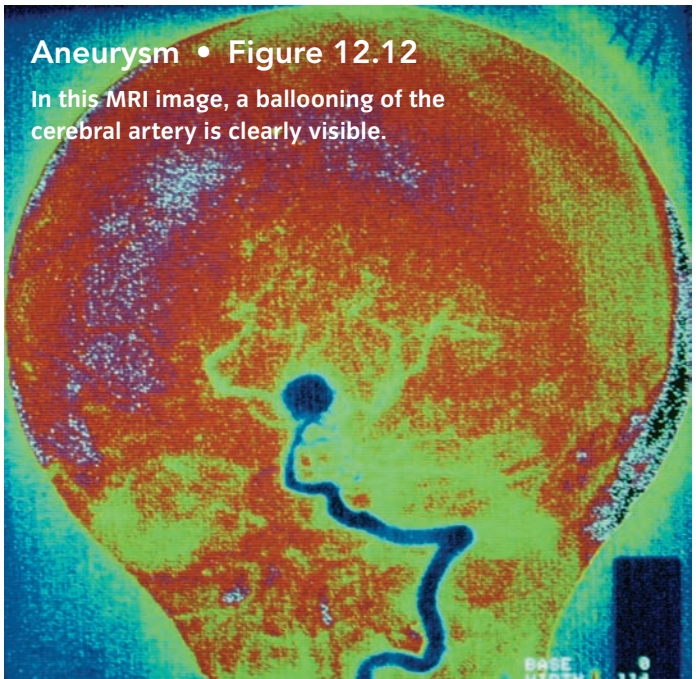
Artery Damage Is a Major Cause of Mortality and Disability

Atherosclerosis (literally "hardened vessels") is another disease of the blood vessels. When **plaques,** fatty deposits of cholesterol, accumulate inside the vessel walls, they narrow or block the lumen, reducing blood flow, as shown in Figure 12.11. More serious complications can arise if the plaque causes a clot to form within the vessel. A clot that is attached to the vessel wall is called a thrombus; if it loosens and floats in the bloodstream, it is called an **embolism**. This floating clot can lodge in a smaller vessel, completely blocking blood flow and causing tissue death.

An **aneurysm** occurs when a vessel wall balloons under pressure, forming a weak spot that can burst with pressure generated by each heartbeat. See Figure 12.12. Burst aneurysms are usually fatal. Because arteries are not exchange vessels, aneurysms can sometimes be repaired before they burst by replacing the ballooned area with plastic tubing.

An embolism or aneurysm in the brain causes stroke. Whether the problem is a blockage or excess bleeding, stroke starves the tissues fed by the affected artery of oxygen and nutrients. Initial symptoms of stroke include sudden difficulty speaking, blindness in one eye,

Aneurysm • Figure 12.12



In this MRI image, a ballooning of the cerebral artery is clearly visible.

and numbness and/or weakness, usually on one side of the body. Stroke can also cause **aphasia** (loss of speech), loss of fine motor control, paralysis, or even death. New emphasis on quick treatment of strokes has reduced the disability, but many of the 700,000 Americans who have a stroke each year do have widespread brain damage.

Heart Attacks Have Causes and Consequences

Perhaps the most fearsome cardiovascular disorder is **heart attack**, the death of a portion of the heart muscle due to a lack of oxygen. Heart attack, or **myocardial infarction** (MI), causes one in five deaths in the United States. Each year, the population of the United States suffers more than 1.2 million nonfatal heart attacks; of those patients, 40% will die within one year.

Dead cardiac tissue ceases to conduct electricity, so the contraction impulse cannot pass. A ventricle that cannot contract completely cannot move blood efficiently, and the result is reduced cardiac output.

MI usually occurs when plaque in a coronary artery occludes the blood flow. While the plaque is forming and blood flow is diminishing, the heart tissue may act like a cramped muscle. The pain from this temporary loss of oxygen is usually described as a crushing feeling in the chest, pain that radiates through the chest and left arm, or numbness in the left arm. This condition is called **angina pectoris**, or simply angina.

Angina can be controlled with nitrate drugs.

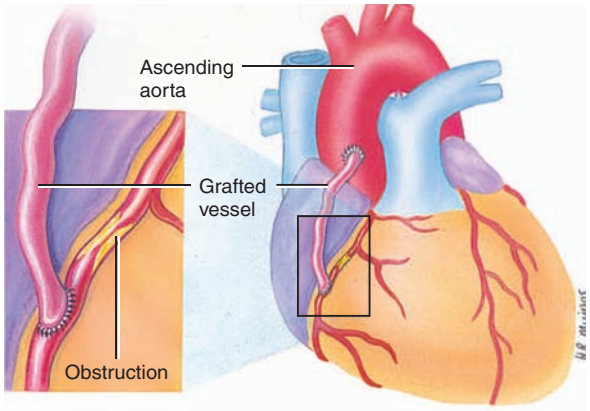
Angina can arise when the heart is working hard, such as during strenuous exercise, or when it is stressed by, for example, smoking cigarettes. This "**stable angina**" can be treated by reducing activity and/or quitting smoking. **Unstable angina**, in contrast, appears with no apparent stimulus and is often an early warning of impending heart attack. Fortunately, people with unstable angina often think they are having a heart attack and seek immediate medical attention.

Angina may be controlled with nitrate drugs, such as nitroglycerine and isosorbide, which relax cardiovascular smooth muscle. As the smooth muscle in the walls of the coronary arteries relaxes, blood pressure decreases, and blood can flow more smoothly past the obstructive plaque.

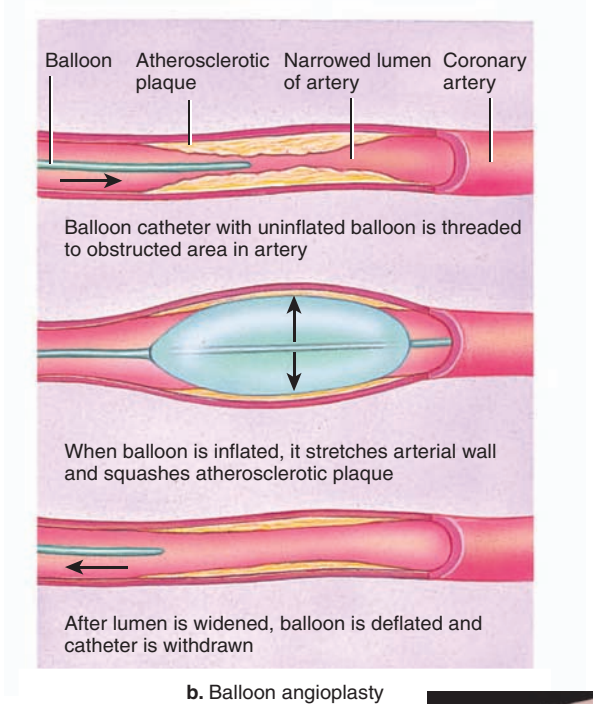
There are several surgical options.

If medication does not restore a normal lifestyle, surgical procedures may be recommended, including **balloon angioplasty**, placement of a **stent**, or **bypass surgery**, as shown in Figure 12.13. Balloon angioplasty pushes soft, fatty plaque against the

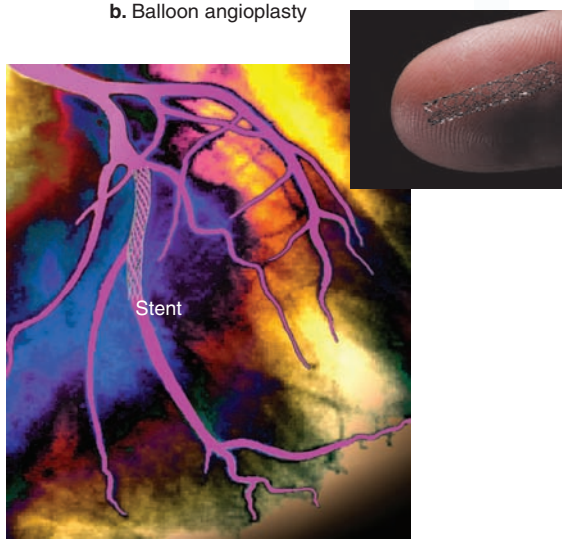
Surgical procedures for reestablishing blood flow in occluded coronary arteries • Figure 12.13



a. Bypass surgery



b. Balloon angioplasty



c. Angiogram showing a stent in a coronary artery

vessel wall, reopening the lumen. The physician inserts a catheter with a deflated balloon at the end into the femoral artery and threads the catheter to the occluded coronary artery. When the balloon is inflated, the lumen expands.

Balloon angioplasty can fail if the plaque does not stick to the vessel wall. Stents, which look like tiny rolls of chicken wire, are designed to overcome this difficulty. A stent supports the arterial walls, permanently opening the vessel to improve blood flow. A stent may be coated with medicine to block plaque buildup; as the medicine leaches from the stent, it supplies a constant dose exactly where it is needed.

If the coronary artery is physically damaged or the plaque buildup is severe, bypass surgery may be required. This is open-heart surgery and is obviously much more invasive than angioplasty. Surgeons break the breastbone to reach the heart and periodically stop the heart to perform delicate suturing. A section of blood vessel, usually from the femoral vein, is removed to serve as the bypass vessel. (Blood return from the legs is not hindered, because the venous system includes many **anastomoses** that provide alternate pathways for blood return.) The surgeons suture a small length of femoral vein around the blockage in the coronary artery, creating something that works like a highway detour: Blood bypasses the congestion and returns to normal circulation beyond the blockage. Each detour counts as one bypass, so a triple bypass surgery involves three detours. Bypass surgery is usually highly effective, but recovery is much slower than after balloon angioplasty or stent placement, due to the major thoracic surgery and the healing required in the leg.

anastomoses Networks or connections between two or more vessels.

When the heart is severely compromised, an artificial heart can be implanted as a bridge to sustain the patient until a suitable human heart becomes available. See *What a Scientist Sees: Is It Possible to Replace Organs with Machines?*

WHAT A SCIENTIST SEES

NATIONAL GEOGRAPHIC

Is It Possible to Replace Organs with Machines?

Replacing diseased hearts has long been a dream of medical science. The heart may look like a simple pump, but the difficulty of replacing it with metal and plastic emerged in 1983, when dentist Barney Clark received an artificial heart and then died a slow and painful death (in the glare of massive publicity) due to small blood clots created by the replacement heart.

Clark's death raised a slew of thorny ethical questions. Were the doctors justified in performing a transplant with the prototype heart? Were they and Clark medical pioneers, selflessly working to perfect and test a technology that would later benefit thousands of others with failing hearts? Or were those who developed the heart self-promoters who took advantage of a dying man in their search for fame and fortune?

The Clark experience put a damper on the quest for an artificial heart, although some machines are now used as a "bridge" to sustain patients until a suitable heart becomes available for transplant. Another artificial heart was tested—with much less publicity—in 2001; it also had problems.

It's now clear that the best replacement for a human heart is another human heart. Many early heart transplants were rejected by the body's immune system, but the use of immune-suppressing drugs after 1980 has vastly improved success rates. According to the American Heart Association, about 2,000 heart transplants are performed each year in the United States, and many heart transplant recipients enjoy 10 or more fairly normal years after the surgery.

Think Critically

1. Why did the artificial hearts cause small blood clots?
2. What is structurally different about these hearts that might cause blood cells to become damaged and initiate a clot?
3. Why are researchers still interested in creating an artificial heart, if human heart transplants can be done successfully?

Congestive Heart Failure Is Due to a Weak Heart

With age, many hearts simply weaken and fail to push enough blood through the circulatory system. Such a condition, called **congestive heart failure**, is increasingly common now that more people are living deep into old age. A weakened left ventricle fails to move the blood, allowing fluid to back up and leak into the lungs, causing **pulmonary edema**. As the blood flow slows, fluid also builds up elsewhere. Congestive heart failure is named for the resulting congestion in the thoracic cavity. When this fluid presses against the heart, beating becomes even more difficult.

Heart failure, unlike angina or MI, is a gradual disease. As the heart weakens, the body attempts to compensate. The heart itself expands, enlarging the volume of each ventricle. Enlarged volume requires more muscle mass to push the blood, causing a further expansion in the heart. As the heart continues to weaken, **tachycardia** pushes more blood through the body, until the heart cannot maintain the rapid pulse. Symptoms of congestive heart failure include fatigue, difficulty breathing, tachycardia, and possibly even death as fluid builds up in the lungs and drowns the respiratory membranes.

tachycardia Resting heart rate above 100 beats per minute.

When Veins Become Visible They Function Less Effectively

Not all cardiovascular diseases are fatal. **Varicose veins** and **spider veins** are unsightly and can be painful. Varicose veins are distensions of the venous walls near valves. As the blood moves into the veins, it pools against the valves. If the walls of a vein are weak due to disease or genetics, the vessel will expand. More blood will move into the distended area with each heartbeat without moving up toward the heart, pushing the walls out even farther. The vein eventually pops out of the musculature and becomes visible as a bluish wrinkled cord directly beneath the skin. The varicose portion of the vein can be removed surgically if it becomes too painful or unsightly.

Spider veins are less visible because they involve venules, not veins. These surface venules fill with blood but do not empty. They are visible through the skin as pale purple or blue tracings and usually occur in small to large patches on the face or thighs. Treatment for spider veins is purely cosmetic, and involves injecting the blocked venule with sterile saline solution to displace the pooled blood.

The exact cause of these two venous disorders is not known, but they do run in families. More women suffer varicose veins than men, and hormonal changes are often implicated. Many women develop varicose veins or spider veins during pregnancy.

Even the Athletic Heart Can Fail

It's a paradox. People exercise to improve their overall health and their CV systems. Yet once in a while, even highly trained athletes keel over from heart attacks. A series of studies over the past 20 years found that extreme athletic effort does seem to raise the risk of heart attack, at least for about 24 hours after the event. They also show, however, that most of the stricken athletes began their careers with mild, undiagnosed heart disease.

A key danger is hypertrophic cardiomyopathy (HCM)—a syndrome of heart myocardium "overgrowth" that usually can be detected with ultrasound examination. In 1993, Boston Celtics All-Star Reggie Lewis collapsed during a routine workout, and most evidence leads to the conclusion that he had HCM.

Another preexisting condition that can cause athletic heart failure is atherosclerosis—hardened arteries that suffer an embolism or aneurysm during the event. However, spasms of the coronary arteries, deformed valves, and other common causes of MI are also to blame. Arrhythmias—erratic heart rhythms—can also cause athletic heart failure, because extreme exertion can sometimes trigger a fatal arrhythmia.

On a tragic day in November 2007, during the running of the New York City marathon, two runners died within hours of each other. Ryan Shay was competing in Olympic marathon trials in Central Park when he died of a heart attack. Dr. Matthew Hardy, a biologist, later completed the marathon and collapsed when he returned home. He was diagnosed by a New York City coroner as having advanced atherosclerosis.

Can extreme exercise damage the heart? Most experts say that exercise helps the heart and overall CV system by strengthening cardiac muscle and the vasculature and by improving the efficiency of circulation and respiration. However, one line of evidence suggests that extreme exercise can sometimes damage the heart: A few recent studies have found the enzyme troponin I

in athletes' blood after endurance events. Troponin I in the blood is considered an indication of death of heart muscle cells.

Long-term studies of competitive marathon runners show that only a few runners have died of coronary artery disease or unusual coronary anatomy. However, all runners (and exercisers) are urged to report any cardiac symptoms to a doctor.

CONCEPT CHECK STOP

1. **What** is a stroke? Does risk of stroke increase with high blood pressure, arterial damage, or both?
2. **What** are the risk factors for heart attack?
3. **What** can happen if venous walls become weak?
4. **What** role does lifestyle play in cardiovascular disease?

12.5 Blood Consists of Plasma and Formed Elements

LEARNING OBJECTIVES

1. **Explore** the role of plasma in blood.
2. **List** the formed elements in blood.
3. **Describe** the functions of white blood cells.
4. **Explain** how red blood cells carry oxygen to the tissues.
5. **Discuss** the physiological basis of blood typing.
6. **Describe** how clots form.
7. **Describe** the general pathology of anemia and blood-borne pathogens.

Some people are squeamish about blood. They do not like to see it outside the circulatory system, and the mere thought of it can weaken their knees. This is unfortunate, because blood is a unique and essential connective tissue. It is composed of a liquid portion, the **plasma**, and a solid portion, the **formed elements**, which are mainly cells, as shown in Figure 12.14.

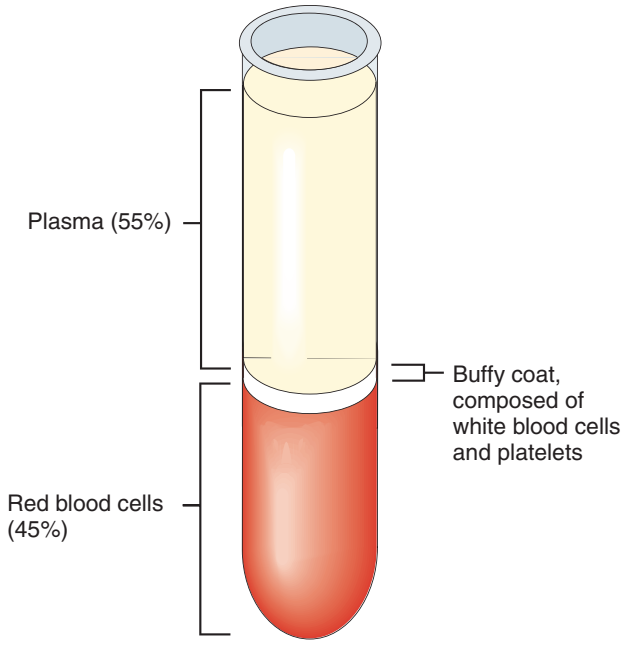
Blood is critical to maintaining homeostasis:

- Blood regulates the internal environment of the body by diffusing ions and other materials into the interstitial fluid.
- It forms clots to prevent blood loss at injuries.
- Blood also transports heat between the body core and the skin.
- Dissolved in the plasma are **hormones**, nutrients, and gases that are needed in other areas, so blood serves as a mode of transport for these compounds.
- In addition, the formed elements in the blood deliver oxygen and patrol the body to destroy pathogens. Both specific and nonspecific immunity occur within the blood.

hormones Compounds secreted in one area of the body that are active in another area; usually carried by the blood.

Centrifuge tube of spun blood • Figure 12.14

When blood is spun in a centrifuge, the formed elements settle to the bottom of the tube, leaving the plasma on the top. The red blood cells (RBC) are heavier than the white blood cells, so the white blood cells are found in a small "buffy coat" above the packed red blood cells.



Appearance of centrifuged blood

ETHICS AND ISSUES

When Do People Have the Right to Refuse a Blood Transfusion?

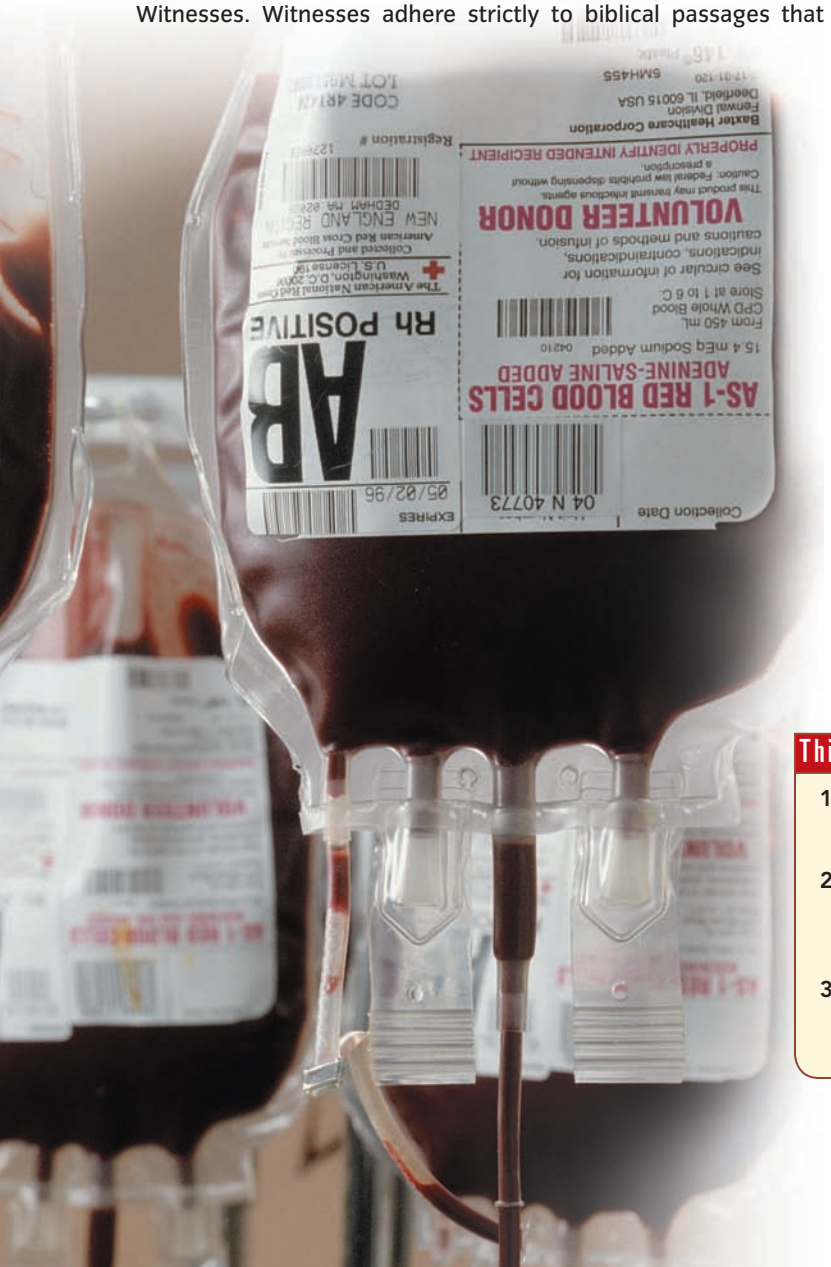
The short answer to this question is that any adult can refuse a blood transfusion for any reason. However, this conflicts with doctors' obligation to do everything possible to save a life. Both the legal system and medical practice have been wrangling with this conflict for many years.

Some people refuse to receive blood from others because they are afraid that they might contract a blood-borne disease, such as human immunodeficiency virus (HIV) or hepatitis. Others have had a negative experience with a prior blood transfusion, such as an anaphylactic (sudden and severe allergic) reaction. These health concerns can usually be put to rest with competent medical care and blood screening.

Most people who refuse transfusions do so out of religious conviction, and the majority of these individuals are Jehovah's Witnesses. Witnesses adhere strictly to biblical passages that they interpret as forbidding the use of blood that has been removed from the body. Practicing Witnesses don't accept transfusions of whole blood or any of the four primary components of blood: red blood cells (RBCs), white blood cells (WBCs), platelets, or plasma. This applies not only to blood from others but also to transfusions of their own blood, removed earlier and used during surgical procedures.

The area in which Witness beliefs come into most direct conflict with the legal and ethical obligations of medical personnel involves pregnant mothers, children, and teens. Although U.S. law allows parents to make health-care decisions for their children, it also allows for children to be removed from their parents' custody in cases of parental neglect. In many instances, courts have ruled that Witness parents' refusal to allow a transfusion for a critically ill child constitutes neglect and have placed the child in temporary state custody for the purpose of undergoing necessary medical procedures.

The most severe conflicts have occurred when pregnant mothers have refused life-saving transfusions. Such situations have led to some highly specific legal rulings. For example, several courts have ruled that a pregnant woman does not give up her right to refuse transfusions just because she is carrying another life, but that as soon as the fetus has been delivered, the state has the right to overrule her and allow a doctor to intervene with fetal or maternal transfusions.



Critical Reasoning Issues When medical practices conflict with religious beliefs, it can be difficult to apply critical reasoning. Health-care providers and legal experts have to use whatever tools are available to both preserve life and respect patients' rights.

Think Critically

1. Do you agree or disagree with the legal distinction between a woman with an unborn fetus and a woman with a just-born fetus?
2. Do you think teenagers or their parents should have the right to refuse a blood transfusion on religious grounds, or should courts treat anyone under the age of 18 as a child for the purpose of receiving a life-saving blood transfusion?
3. If a person refuses a blood transfusion on nonreligious grounds but stated such a preference in a formal "advance directive" document, should doctors abide by the patient's decision?

None of these functions is reason to fear blood; instead, they indicate just how remarkable this tissue is. Many of us will require a blood transfusion in the course of our lives, although some of us will reject the idea of a transfusion. See *Ethics and Issues: When Do People Have the Right to Refuse a Blood Transfusion?* on the previous page for more on this topic.

Plasma Is 46–63% of Total Blood Volume

Plasma itself is 92% water, 7% dissolved proteins, and 1% **electrolytes**, nutrients, and wastes. The proteins help maintain blood's osmotic pressure, so water will remain inside the vessels instead of diffusing into tissues. The proteins are too big to pass through capillary walls, so they stay in the blood. The protein albumin is particularly important in maintaining osmotic pressure. If the albumin level drops, osmotic pressure of the blood shifts, forcing water from the blood into the tissues, causing edema. Albumin also binds with several drugs, including penicillin, helping with the transport of those drugs.

electrolytes Compounds that form a solution that can conduct electricity.

colony-stimulating factors Blood-borne compounds that cause cells in the bone marrow to produce new blood cells.

erythrocytes Red blood cells.

leukocytes White blood cells.

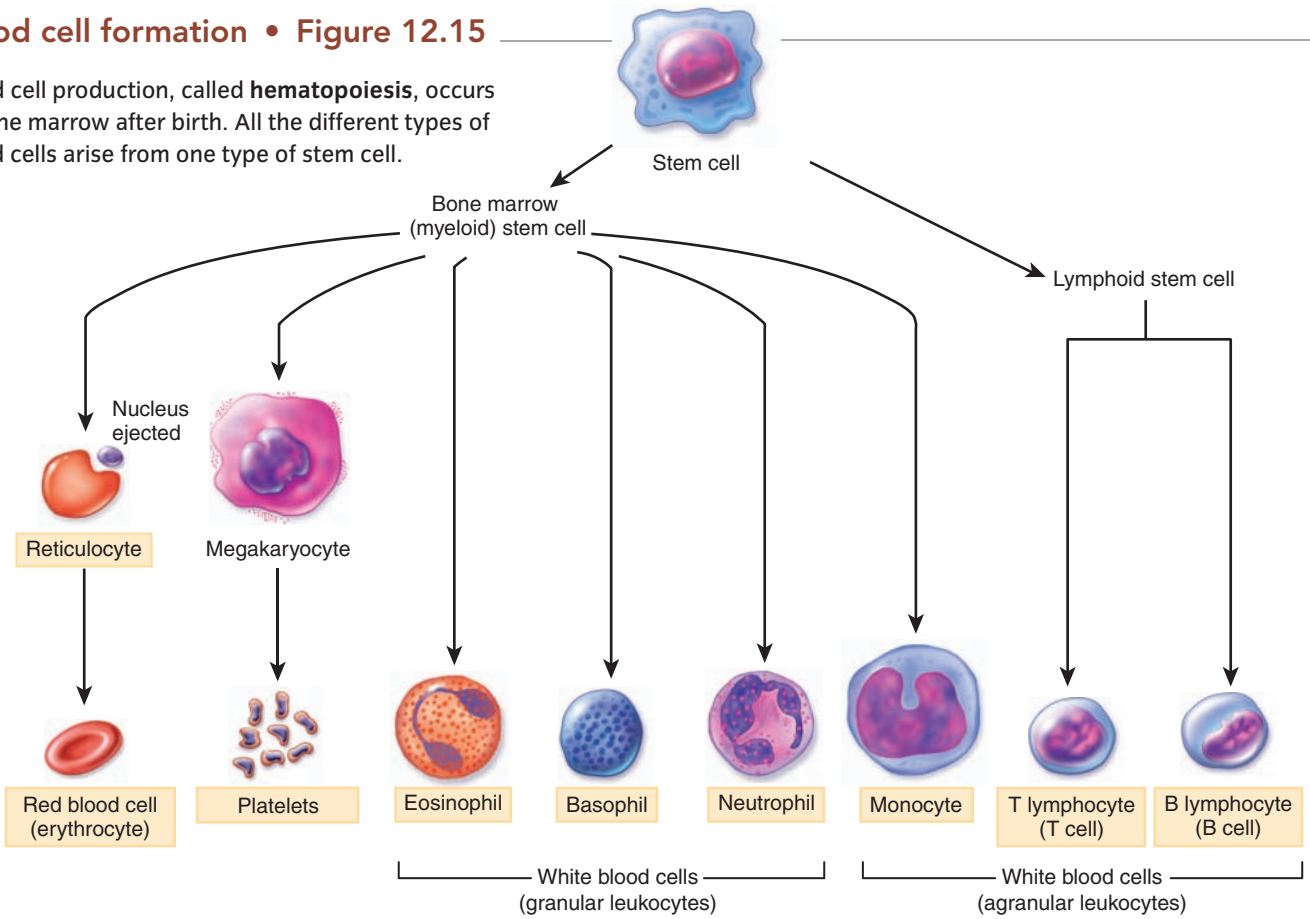
The electrolytes in the plasma include sodium and potassium, both key ions for cell functioning. The nutrients in plasma include carbohydrates and amino acids, and the wastes carried in the plasma are mostly urea, carbon dioxide, and lactic acid. Plasma rivals seawater in its complexity!

The Formed Elements of Blood Are Cells and Cell Fragments

The formed elements of the blood are cells or bits of cells that originate in the red bone marrow. See **Figure 12.15**. In adults, red marrow is located within the epiphyses of the long bones, in the hip and sternum. Under the direction of hormones and **colony-stimulating factors**, blood stem cells differentiate into **erythrocytes** (red blood cells or RBCs), platelets, or **leukocytes** (white blood cells or WBCs). Ninety-nine point nine percent of the formed elements are red blood cells, which give blood its red color. The other 0.1% are white blood cells and platelets.

Blood cell formation • Figure 12.15

Blood cell production, called **hematopoiesis**, occurs in bone marrow after birth. All the different types of blood cells arise from one type of stem cell.



White Blood Cells Are Defensive Cells

Leukocytes (white blood cells) are specialized for defense, and though not abundant, they are critical to the immune system. There are approximately 5,000 to 11,000 white blood cells per mm^3 of blood, compared to the 4 to 6 million red blood cells per mm^3.

There are five types of white blood cell (WBC):

- Three granular cells: **neutrophils**, **eosinophils**, and **basophils**, and
- Two agranular cells: **lymphocytes** and **monocytes**.

Granular white blood cells have dark granules when stained. "Granular" means that when the cells are stained, dark granules appear in the cytoplasm under a microscope. The odd names of the granulocytes (granular leukocytes—neutrophil, eosinophil, and basophil) reflect what happens when they are placed in Wright's stain, a mixture of stains used to identify white blood cells. Neutrophil granules become stained with the neutral stain (their granules "like" neutral stain, which is the literal translation of "neutrophil"). Eosinophil granules stain a bright orange-pink, the color of the eosin portion of the stain. Basophil granules take on the basic (pH 11) stain color, nearly black.

Agranular white blood cells have no granules when stained. Agranulocytes (agranular leukocytes) contain no granules in their cytoplasm. Lymphocytes are small, round cells with little visible cytoplasm. They come in two varieties: B cells that produce antibodies and T cells that are usually directed against a pathogen. As discussed in Chapter 10, the AIDS virus attacks some of the T cells, causing a drop in immunity. The monocytes are the largest of the white blood cells, with quite a bit of cytoplasm surrounding a large, kidney-shaped nucleus, as seen in Figure 12.16.

White blood cell proportions usually stay constant. The proportions of leukocytes remain fairly constant in a healthy individual. Neutrophils make up the majority of circulating WBCs, with lymphocytes a close second. Monocytes are the third most common WBC, followed by eosinophils and then basophils. You can remember the order with this catchphrase: "Never let monkeys eat bananas." (n = neutrophils, l = lymphocytes, m = monocytes, e = eosinophils, and b = basophils)

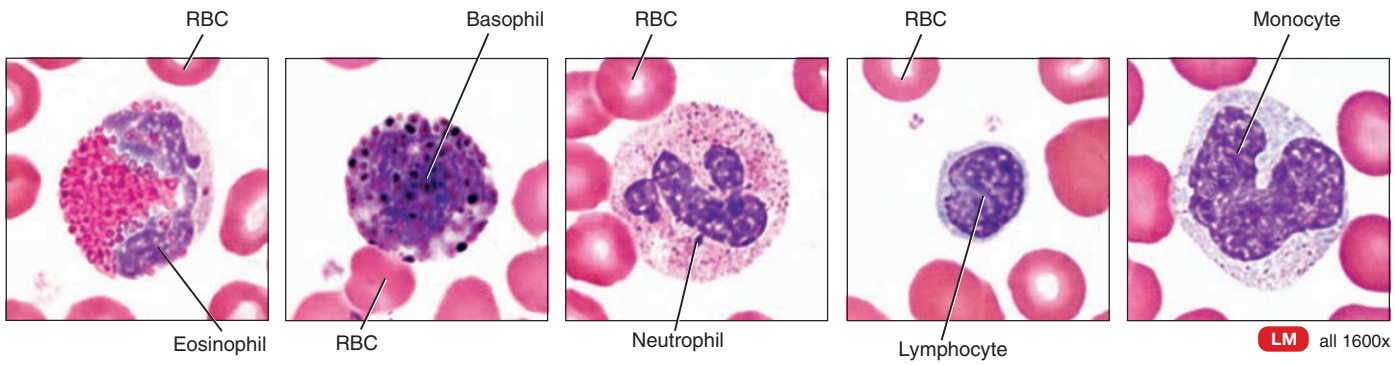
Each cell has a specific function in warding off pathogens. When necessary, specific populations of WBCs increase, altering the overall proportions. The proportion of white blood cells gives an indication of the type of pathogen that is present. See Table 12.1 for a physical description and the main function of each type of WBC.

Red Blood Cells Carry Oxygen

Erythrocytes, or red blood cells, transport oxygen to the tissues and are by far the most common blood cells. A red blood cell (RBC) is little more than a membrane-bound sac of **hemoglobin**, a protein that contains the pigment heme. Each RBC carries approximately 200 million hemoglobin molecules. Each of these molecules

Leukocyte comparison • Figure 12.16

Eosinophils, basophils, and neutrophils have more defined granules when stained, whereas lymphocytes and monocytes do not.



a. Eosinophil **b.** Basophil **c.** Neutrophil **d.** Lymphocyte **e.** Monocyte

Summary of formed elements in blood Table 12.1

Name and Appearance	Number	Characteristics*	Functions
Red Blood Cells (RBCs) or Erythrocytes 	4.8 million/μL in females; 5.4 million/μL in males	7–8 μm diameter, biconcave discs. without nuclei; live for about 120 days.	Hemoglobin within RBCs transports most of the oxygen and some of the carbon dioxide in the blood.
White Blood Cells (WBCs) or Leukocytes	5,000–10,000/μL	Most live for a few hours to a few days.†	Combat pathogens and other foreign substances that enter the body.
Granular leukocytes:			
Neutrophils 	60–70% of all WBCs	10–12 μm diameter; nucleus has 2–5 lobes connected by thin strands of chromatin; cytoplasm has very fine, pale lilac granules.	Phagocytosis. Destruction of bacteria with lysozyme, defensins, and strong oxidants, such as superoxide anion, hydrogen peroxide, and hypochlorite anion.
Eosinophils 	1–3% of all WBCs	10–12 μm diameter; nucleus usually has 2 lobes connected by a thick strand of chromatin; large, red-orange granules fill the cytoplasm.	Combat the effects of histamine in allergic reactions, phagocytize antigen–antibody complexes, and destroy certain parasitic worms.
Basophils 	0.5–1% of all WBCs	8–10 μm diameter; nucleus has 2 lobes; large cytoplasmic granules appear deep blue-purple.	Liberate heparin, histamine, and serotonin in allergic reactions that intensify the overall inflammatory response.
Agranular leukocytes:			
Lymphocytes (T cells, B cells, and natural killer cells) 	25–33% of all WBCs	Small lymphocytes are 6–9 μm in diameter; large lymphocytes are 10–14 μm in diameter; nucleus is round or slightly indented; cytoplasm forms a rim around the nucleus that looks sky blue; the larger the cell, the more cytoplasm is visible.	Mediate immune responses, including antigen–antibody reactions. B cells develop into plasma cells, which secrete antibodies. T cells attack invading viruses, cancer cells, and transplanted tissue cells. Natural killer cells attack a wide variety of infectious microbes and certain spontaneously arising tumor cells.
Monocytes 	3–8% of all WBCs	12–20 μm diameter; nucleus is kidney shaped or horseshoe shaped; cytoplasm is blue-gray and has foamy appearance.	Phagocytosis (after transforming into fixed or wandering macrophages).
Platelets 	150,000–400,000/μL	2–4 μm diameter cell fragments that are destroyed after 10 days; contain many vesicles but no nucleus.	Form platelet plug in hemostasis; release chemicals that promote vascular spasm and blood clotting.

*Colors are those seen when using Wright's stain.

Some lymphocytes, called T and B memory cells, can live for many years once they are established.

has at its center four atoms of iron. This iron picks up oxygen (it rusts, in essence) in an environment where the oxygen content is high and releases oxygen where oxygen is scarce. Hemoglobin responds to the varying pressures of oxygen in tissues and blood. This setup is perfect, because the body needs to transport oxygen from the lungs (where oxygen concentration is high) to the tissues (where the concentration is low). Hemoglobin is so perfect, in fact, that it is the only respiratory protein found in vertebrates; the same protein also carries oxygen for fish, whales, and frogs. Hemoglobin also appears throughout the **invertebrates**, where it floats in the blood, or **hemolymph**, of some insects, clams, and worms.

invertebrate Organism without a vertebral column, such as an earthworm, crab, or starfish.

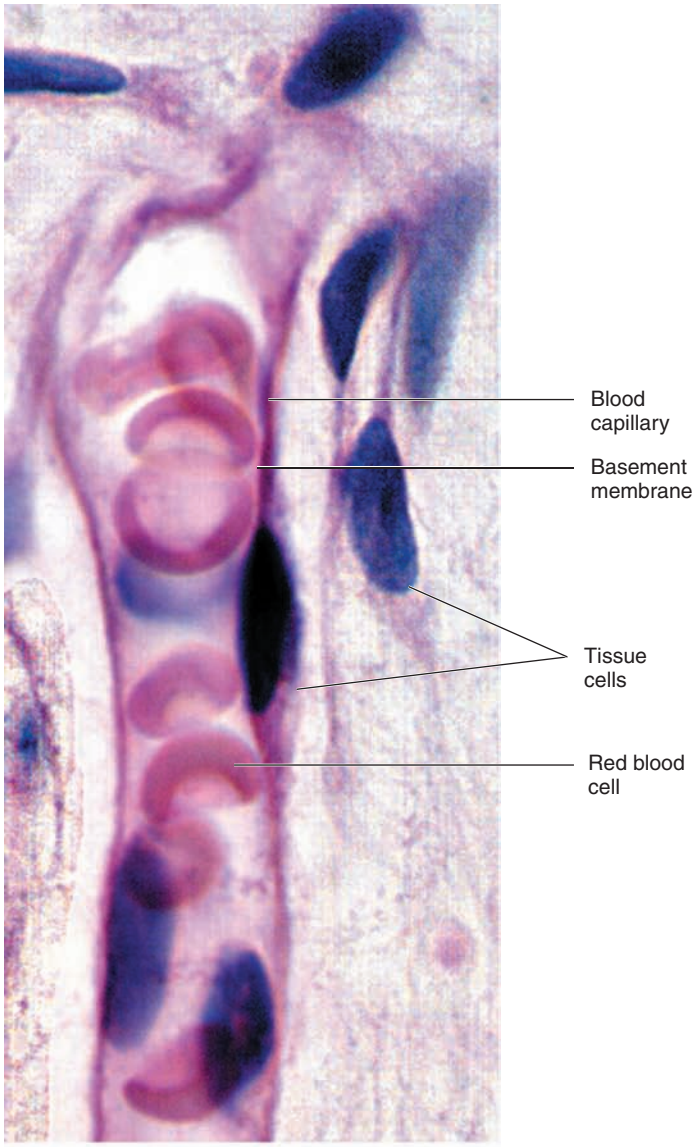
hemolymph An oxygen-carrying fluid that circulates through the tissues of many invertebrates with open circulatory systems.

Hemoglobin also responds to changes in pH and temperature. In low pH or high temperature, both of which occur in active muscle, hemoglobin drops its oxygen more readily, so that the RBC delivers the oxygen exactly where it is needed. No wonder this respiratory protein is found in so many organisms.

Red blood cells are unique in many ways. As the immature red blood cell develops, it kicks out the nucleus to make room for more hemoglobin. Without a nucleus, the cell can neither repair itself nor direct cellular activities, including such basics as cellular respiration. Red blood cells do not survive long in the circulatory system. All the pressure from the left ventricle of the heart races the RBCs through the vessels and squishes them, one cell at a time, through the capillary beds—see **Figure 12.17**. While passing through these beds, RBCs not only drop their oxygen, but they also suffer physical damage, which cannot be repaired in the absence of a nucleus.

RBCs circulate for approximately 120 days before they are damaged enough to need removal from the circulatory system. The spleen and liver are responsible for removing these cells, breaking them down, and recycling their constituent minerals and proteins. An estimated 2 million RBCs are broken down per second. Because we do not run out of RBCs, we must produce them at the same rate: an incredible 2 million cells per second.

Red blood cells crowding through a capillary • Figure 12.17



Hormones stimulate RBC production. The rate of **erythropoiesis** (RBC formation) in red bone marrow is affected by hormones and environmental need. When blood oxygen drops, the kidneys are stimulated to produce erythropoietin, a hormone that stimulates RBC production. Because the presence of more red blood cells translates into more oxygen-carrying capacity, athletes can use this physiological fact to improve their train-

erythropoiesis The formation of red blood cells (*erythro* = red, *poiesis* = to form).

ing. Because oxygen is scarce at higher altitudes, many athletes train at higher elevations just to stimulate RBC production. Some athletes have also used commercial erythropoietin, or EPO, to do the same thing, in a procedure known as blood doping. Although this hormone does increase RBC production, the performance advantage is unproven, and EPO is banned in many sports. See *I Wonder… How Does Blood Doping Work?*

Red Blood Cell Surface Proteins Determine Blood Type

Red blood cells, like other somatic cells, have many marker proteins on their surfaces, but the most important set is the markers that determine blood type. Blood type is described as A, B, AB, or O. Although you probably know your blood type, you may have no idea what those letters mean.

I WONDER...
How Does Blood Doping Work?

Blood doping, also known as blood loading, is really several procedures with a single goal: to increase the number of red blood cells (RBCs) per unit of blood, which in turn will increase the supply of oxygen to the muscles. Blood doping seems to be very effective; however, it is also very dangerous.

"Old school" blood dopers often used transfusions of their own blood (autologous transfusion) or someone else's blood (homologous transfusion) to increase their RBCs. "New school" dopers inject the hormone erythropoietin (EPO) to stimulate RBC production "naturally." This is the natural pathway for increased RBC production, but there is no physiological basis for the increase. The body does not need the extra RBCs. Blood doping therefore can be extremely harmful. The high concentration of RBCs thickens the blood, straining the heart and making it easier for clots to form.

Many professional athletes, especially cyclists, have been suspected of blood doping. Because blood doping can improve performance in activities that require endurance, many athletic organizations are concerned not only about its health risks but also about the unfair advantage it might create. With these concerns in mind, cycling's international governing body has recommended that each cyclist have a "blood passport," a medical profile of his or her blood that would make it possible to determine whether the RBC count is the same after a race as before it. However, since false positive tests for EPO are common (it is a natural hormone), many cyclists have successfully challenged findings that they were using EPO to dope their blood. Now the opposite problem has emerged: A June 2008 study in the *Journal of Applied Physiology* says that the urine test used in the Olympics and the Tour de France to detect blood doping is often likely to miss it. Professor Charles E. Yesalis at Pennsylvania State University says the anti-doping authorities "remind me of little boys whistling in the graveyard." In sum, although blood doping is a dangerous practice, in the world of professional sports where winning seems to be the main goal, competitors remain willing to accept the health risks associated with it.

A, B, and O were arbitrarily chosen to identify the protein markers on the surface of your red blood cells. People with the "A" marker have type A blood; people with the "B" marker have type B. Because these traits are **codominant**, some people have both A and B markers, which we call type AB blood. Those with neither A nor B markers have type O blood, which represents the condition described as "no markers."

codominant Neither form of a gene will overshadow the other; when both forms are present, the individual will express both equally.

Recent findings, however, indicate that type O blood has the precursor to the A and B markers on its surface. This precursor, called H substance, is modified to form the A and B antigens on the surface of types A, B, and AB blood, as seen in Figure 12.18. Apparently, people with type O do not modify the H substance, leaving it in its original form, able to trigger antibodies to both A and B antigens.

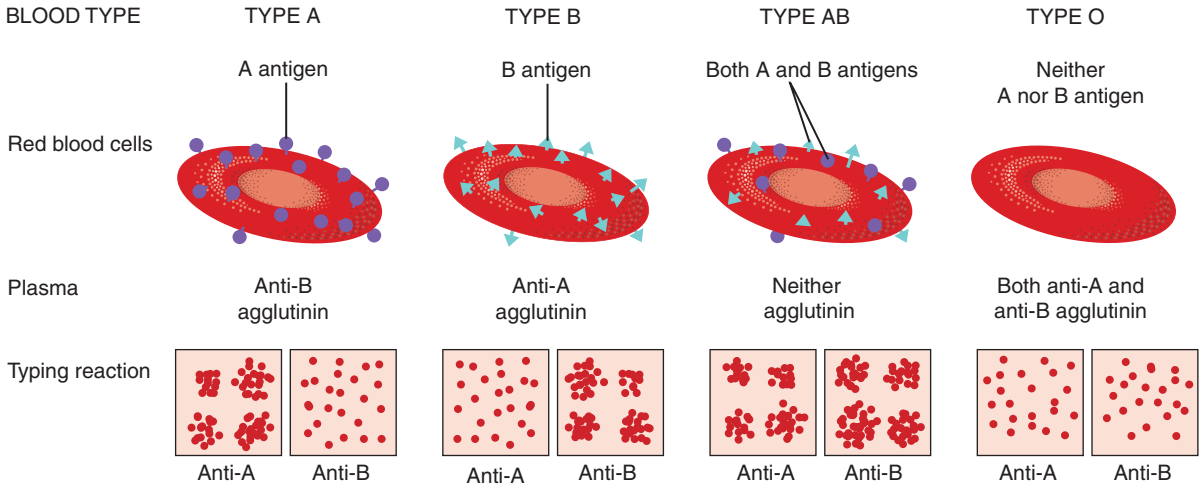
Despite certain dieting fads, the A, B, and O blood markers are important only when we must receive blood. The plasma of people with type A blood contains an anti-B **agglutinin** that will clump B blood. Similarly, those with type B blood have plasma that contains an anti-A agglutinin, which clumps type A blood. Type O blood carries both anti-A and anti-B agglutinins. This does not harm the individual, because their RBCs have neither marker. It stands to reason that those with type AB blood have neither anti-A nor anti-B agglutinins, because either would agglutinate their blood, with fatal results. If the blood type is not matched before a blood transfusion, a recipient's agglutinins will clump the introduced blood, negating any benefits of the additional blood volume and possibly causing life-threatening problems.

agglutinin Agent that causes cells to clump together or agglutinate.

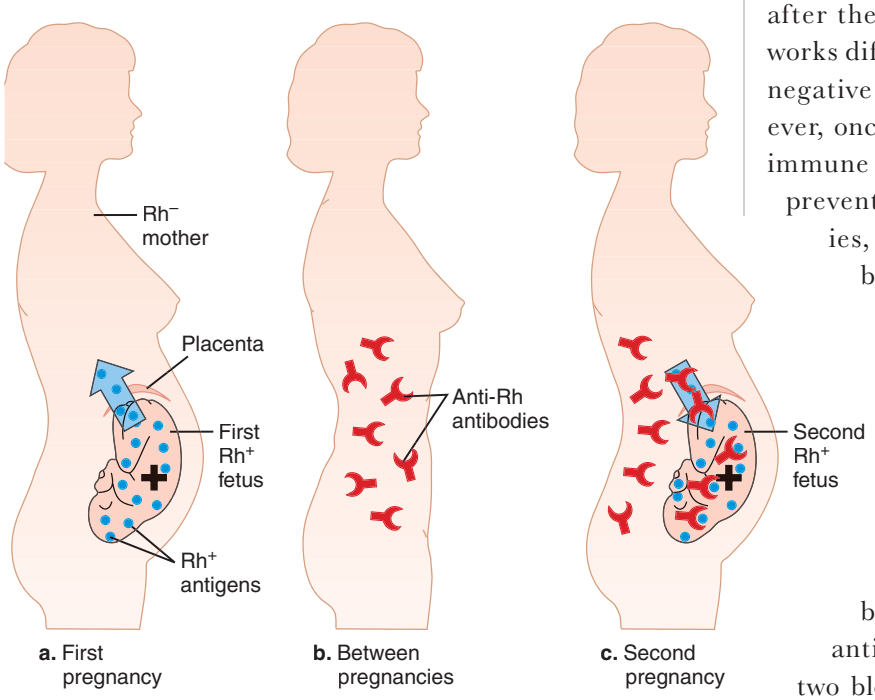
To determine blood type, technicians mix small samples of blood with each type of agglutinin and observe any reaction. If your blood clumps up when mixed with anti-A agglutinin, your RBCs have the surface marker A, and your blood is type A. If no clumping occurs when your blood is mixed with anti-A, you have type B or type O. Samples that clump when mixed with anti-B agglutinins have the B marker and are type B. A sample that reacts with both anti-A and anti-B must have both A and B markers and is thus type AB. Conversely, if no reaction appears with either agglutinin, the sample is type O.

The antigens and antibodies involved in blood typing • Figure 12.18

Blood type depends on which antigens are present or absent on the red blood cell. Plasma contains antibodies that bind with matching antigens and cause clotting. When discussing blood typing, this means that A antigen blood cells can peacefully co-exist with anti-B antibodies (and not clot), and so on. Typing blood requires mixing the red blood cells with anti-A and anti-B agglutinins. A clumping reaction indicates blood type.



The events that lead up to hemolytic disease of the newborn • Figure 12.19



Blood types are genetically based. In the United States, type O blood is more common than type A; however, the proportions of each type differ among ethnic groups. Slightly more than 46% of the Caucasian U.S. population is type O, whereas 38.8% is type A. Types B and AB are much rarer, comprising 11.1 and 3.9% of the population, respectively. Among African Americans, A and B are more evenly distributed: 49% are type O, 27% are type A, 20% are type B, and 4% are type AB. As a comparison, the Native American population is largely type O (79%). Very few Native Americans have type A blood (16%), and even fewer have type B (4%) or type AB (1%).

Because blood types are genetically based, they can be used to identify fathers in paternity suits, to eliminate or incriminate suspects in criminal investigations, and even to study ancient population migrations. A total of 26 blood groups other than ABO have been identified for these pursuits, including the MNS, P, Lutheran (LU), and Kell (KEL).

The Rh factor can complicate pregnancy. Another blood-cell antigen, called **Rh factor**, is either present (Rh positive) or absent (Rh negative) on RBCs. On a blood-type card, Rh factor is the plus or minus sign after the A-B-O designation: "A+" or "O−." Rh factor works differently than ABO, because people who are Rh negative do not ordinarily have anti-Rh agglutinin. However, once they are exposed to Rh-positive blood, their immune system starts to produce anti-Rh antibodies. To prevent complications from anti-Rh-positive antibodies, the Rh factor must be matched: Rh-negative blood should be given to an Rh-negative person to prevent the person from forming anti-Rh agglutinins.

Eighty-five percent of the U.S. population is Rh positive. Rh-negative mothers are at risk of **hemolytic disease of the newborn**, or HDN, as seen in Figure 12.19, if the father is Rh positive. As an Rh-positive child develops in the uterus, fetal blood and maternal blood do not mix, so the mother will not make anti-Rh agglutinin. During birth, however, these two blood supplies may contact each other, in which case the mother will begin to produce anti-Rh antibodies. These antibodies will not affect her, or her first child, but if she becomes pregnant with a second Rh-positive child, her Rh-positive antibodies will cross the placenta and cause agglutination and destruction of this second baby's blood. Rh-negative mothers can be prevented from producing the antibodies that affect the second birth by inoculation with a dose of anti-Rh-positive antibodies **immediately after the first birth**. These antibodies clump the Rh-positive blood and remove it from the mother's blood supply before her immune response is launched.

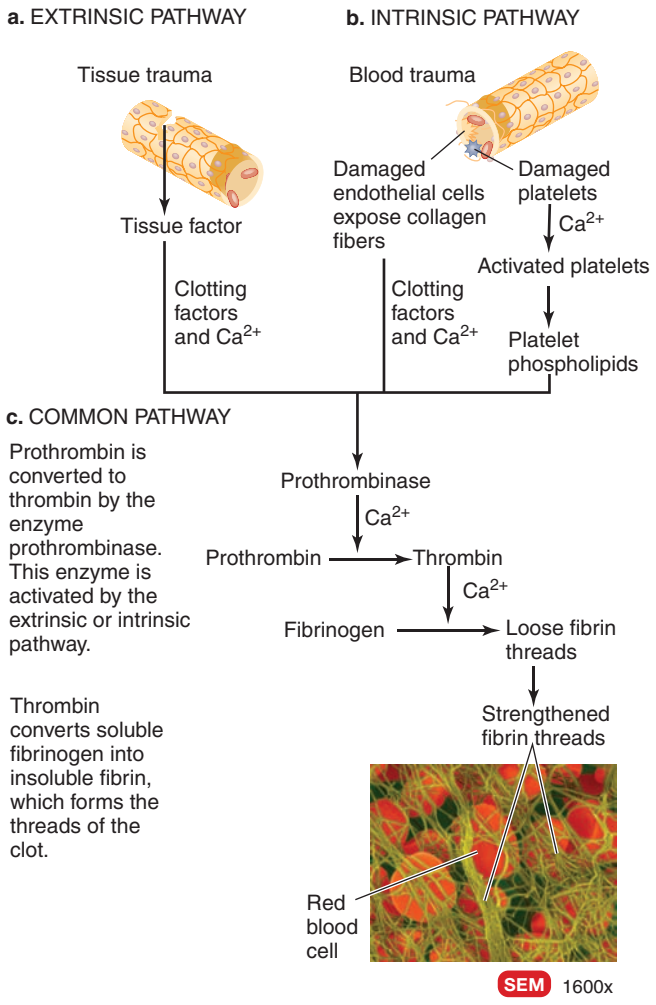
Platelets Govern Blood Clotting

Platelets, the final type of formed element, are not even complete cells, but rather fragments of large cells called **megakaryocytes** that remain in the bone marrow. These huge cells bud pieces from their cytoplasm and release them into the bloodstream, forming more than 200 billion platelets per day. The fragments lack organelles and energy stores, but they do contain packets of physiologically active compounds. Once these compounds are released from the platelet into the surrounding plasma, they begin a series of events leading to the formation of a blood clot, in a process called **hemostasis**.

PROCESS DIAGRAM

THE PLANNER

Clot formation • Figure 12.20



Clotting is necessary for maintaining fluid homeostasis; as we know, severe bleeding is a life-threatening emergency. Clotting is a complicated process in which a series of plasma proteins interact with clotting factors released by the platelets, as shown in Figure 12.20.

1. Clotting begins when a blood vessel is damaged, turning its normally smooth interior rough. These rough edges catch platelets flowing past, forming a **platelet plug** that may seal the wound without need for a true clot. A platelet plug is what prevents bleeding from a paper cut.
2. If the rip is too large for a platelet plug, a clot will form as the stuck platelets rupture with the pressure of the passing blood and release compounds that react with plasma components. These interactions begin a series of events that continue until blood flow ceases.
3. The damaged tissue and trapped platelets release **prothrombinase activator**, which converts the plasma protein **prothrombin** into its active form, **thrombin**.
4. Thrombin, in turn, activates the plasma protein **fibrinogen**, forming long thin fibers of **fibrin**. The fibrin threads get caught in the rough edges of the torn vessel, creating a net. As blood flows through the fibrin net, red blood cells get trapped. More fibers are delivered by fresh plasma that reaches the wound. The new fibrinogen interacts with fresh thrombin, and the clotting cascade continues until the plasma stops flowing and ceases, bringing more protein.
5. When plasma stops flowing, clotting has succeeded at stopping the bleeding. Clotting is a rare example of positive feedback in the body.

Sometimes it is necessary to prevent blood clotting, or at least lower the possibility of forming a clot. Often blood thinners are used for this purpose. See *Health, Wellness, and Disease: Blood Thinners: How and Why* to learn more.

Blood Can Suffer Many Disorders

Because blood is so vital, when something goes wrong with it, our quality of life is severely diminished. Disorders of the blood can be life-threatening, as in leukemia, or they can cause acute disabilities, as in anemia. **Infectious mononucleosis**, commonly called mono, is a common blood disease on college campuses. Mono is caused by the **Epstein–Barr virus** and is transmitted through saliva—hence the popular name of "kissing disease."

Leukemia includes several cancers of the bone marrow.

Perhaps the most frightening blood disorder is **leukemia**, literally: "white blood." Leukemia is a general term for several cancers of the bone marrow. In most leukemias, the white blood cells are shaped abnormally and do not function properly. More than 2,000 children and 27,000 adults in the United States are diagnosed with leukemia every year.

Many symptoms of leukemia are flu-like, and all are related to those nonfunctional white blood cells. Infections take hold more readily and are more persistent. Lymph nodes and the spleen swell in an effort to rid the body of these defective leukocytes. To add to the difficulty, when the bone marrow is pushing out too many white blood cells, it often reduces its output of red blood cells, which reduces the blood's oxygen-carrying capacity, causing fatigue and weakness.

HEALTH, WELLNESS, AND DISEASE

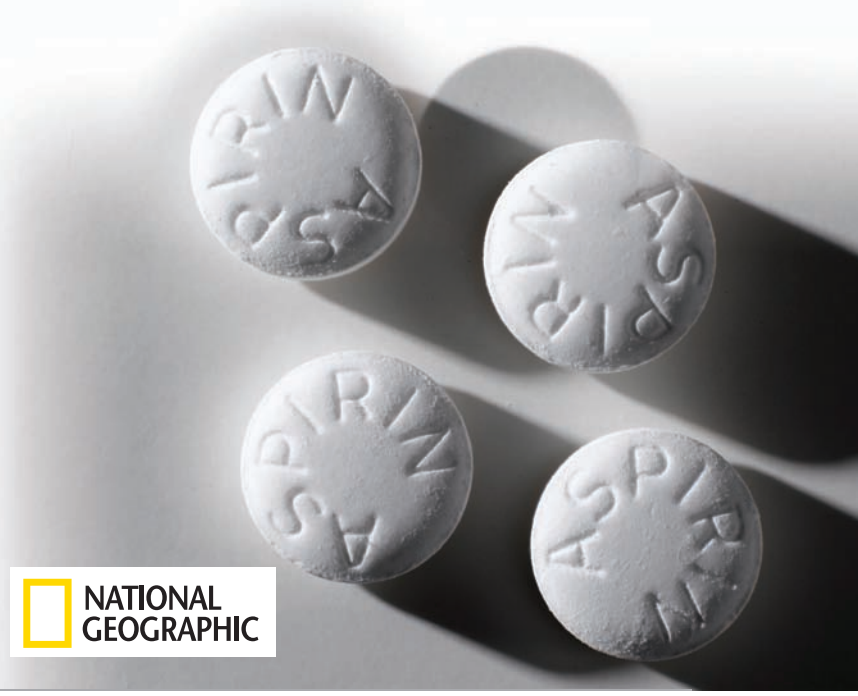
Blood Thinners: How and Why

In order to maintain homeostasis, it is imperative that we not lose too much blood from our bodies. Fortunately, when we are healthy we can easily and quickly form blood clots to prevent not losing too much blood from our cardiovascular system. It seems counter-intelligent, therefore, for anyone to take a drug that prevents this necessary process, and yet blood thinners are routinely prescribed for patients who have had heart valve surgery, congestive heart failure, or venous disorders. Some doctors are even treating complications from obesity with blood thinners. These drugs are usually taken to reduce the risk of heart attack and stroke by preventing clots from forming within undamaged blood vessels. They are effective at preventing new clots from forming, but they cannot break up existing clots.

Coumadin®, Dicumarol®, and Miradon® are the most common brands of blood thinners in the United States. Regular aspirin also helps prevent the formation of blood clots. All of these compounds, including aspirin, belong to a class of drugs called anticoagulants. Anticoagulants do not actually thin the blood; rather, they make it more difficult for the clotting process to occur.

Warfarin sodium is the active compound in Coumadin®. This drug inhibits the liver's ability to take up vitamin K. Vitamin K is required for the formation of four of the clotting cofactors normally circulating in the plasma. If the liver cannot take up sufficient quantities of vitamin K, it will not produce the cofactors necessary for clot formation. Because everyone metabolizes vitamin K at a different rate, it is often difficult to determine the proper dose of Coumadin®. Once the proper level has been calculated, dietary intake of vitamin K must be monitored. Even a small increase in vitamin K uptake can counteract the effects of Coumadin®.

Aspirin has a different mode of action—it irreversibly binds to and inhibits the action of an enzyme responsible for the formation of prostaglandins and thromboxanes. Prostaglandins are inflammatory agents, whereas thromboxanes are instrumental in platelet clot formation. Thromboxanes cause vessels to constrict, and they speed the clumping of platelets at wounds. Without functional thromboxanes, platelets will not stick together at wound sites, and therefore the clotting process will not even begin.



The causes of leukemia are unknown, and although some risk factors have been identified, having these factors does not mean you will necessarily develop leukemia any more than having the risk factors associated with cardiovascular disease means you will have a heart attack. Beyond a family history of the disease, the risk factors include exposure to ionizing radiation from nuclear weapons and nuclear waste and exposure to carcinogens, such as benzene.

Leukemia can be classified by its pattern of onset or by the specific cells affected. **Acute** leukemia appears quickly, filling the blood with extremely immature white blood cells called **blasts**. **Chronic** leukemia appears far more slowly, with blood cells that are more developed but still immature. Both acute and chronic leukemia can affect either **myeloid** or **lymphoid** cells. Both cells mature in the bone marrow, but myeloid cells become the granulocyte form of white blood cells, whereas lymphoid cells mature in the lymph glands and become lymphocytes.

Treatments for leukemia vary depending on the stage of disease and the type of affected leukocytes, but the goal is to move the patient into **remission**—where the disease may remain in the patient's bone marrow, but the leukocytes produced are functionally normal. Treatment—chemotherapy, radiation therapy, bone marrow transplant, or biological therapy—is often successful for a period. Because the disease often reappears, leukemia patients need continual medical monitoring.

Anemia means a shortage of red blood cells.

Anemia is a reduction in the red blood cell population and thus in the blood's oxygen-carrying capacity. The symptoms

of anemia include fatigue, weakness, shortness of breath, and sometimes chest pains like angina. Anemia is easily diagnosed via **hematocrit**. This process is simply a small tube filled with blood and spun in a centrifuge. The percentage of RBCs to total blood volume can then be observed as the cells form a mat of packed cells in the bottom half of the tube. A packed cell level below 42% in adult males, or 38% in adult females, often indicates some form of anemia.

Anemia is classified according to the cause of the red blood cell deficiency:

- **Iron-deficiency anemia.** A shortage of iron leads to fewer hemoglobin molecules for each RBC.
- **Pernicious anemia.** A shortage of vitamin B12 inhibits RBC formation.
- **Aplastic anemia.** The bone marrow does not produce enough stem cells, resulting in this type of anemia.
- **Excessive-bleeding (or hemorrhagic) anemia.** Excessive bleeding reduces RBC counts.
- **Sickle cell anemia.** This inherited disorder misshapes red blood cells, making it harder for them to pass through capillaries.

Carbon monoxide prevents the blood from carrying oxygen.

Carbon monoxide is an odorless environmental poison that prevents the blood from carrying oxygen and can cause death or disability. Carbon monoxide (CO) molecules establish an irreversible bond to hemoglobin, thereby preventing the hemoglobin molecule from carrying oxygen. Red blood cells contaminated with CO float uselessly through the blood until they wear out and are destroyed. Normally, air contains almost no CO, so this irreversible binding is irrelevant. However, the CO concentration increases dramatically in some environments, primarily when fossil fuels are burned and the exhaust fumes are returned to the combustion zone. This increase in concentration can happen if a car runs in a closed garage or a malfunctioning furnace recycles fumes into a residence. Because severe CO poisoning can starve the tissues of oxygen, causing brain damage, myocardial infarction, or death, carbon monoxide detectors (much like smoke detectors) are an affordable and sensible precaution. The first symptoms of CO poisoning are drowsiness and headache. If you suspect carbon monoxide poisoning, move to fresh air and seek medical help. Blood transfusions may be needed to replace carbon monoxide-polluted red blood cells with functional erythrocytes.

Pathogens can live in the blood.

Many pathogens travel in the blood, including **hepatitis**, **HIV**, and other sexually transmitted diseases. The best defense against blood-borne pathogens is to prevent your blood from contacting another person's blood. A key source of infection is unprotected sex, which can tear mucous membranes, causing unintentional contact between the two bloodstreams. Health-care workers are constantly reminded to take precaution around all "sharps," because an inadvertent "stick" with a used needle can spread blood-borne pathogens. To prevent infection through transfusion of tainted blood, blood banks routinely test their stocks of blood for viral contamination. Blood-borne pathogens cause a wide variety of diseases; in each case, treatment aims to eliminate the pathogen from the blood.

The cardiovascular–respiratory connection.

Again and again in this chapter, we have returned to one of the primary roles of the blood: to distribute oxygen and remove carbon dioxide. To do its work, the cardiovascular system must interact closely with the respiratory system, which serves as the point of entry for oxygen and the point of departure for carbon dioxide. If you need more evidence of the tight interaction between the CV and respiratory systems, pay attention to your own body. Take your pulse while resting, and simultaneously count your breaths. Then run up some stairs and repeat. Notice that both your pulse and your breathing have accelerated. To understand what is happening during this interaction of heartbeats and breaths, we must move on to the respiratory system.

CONCEPT CHECK

1. **What** homeostatic functions does plasma provide?
2. **What** are the formed elements in blood?
3. **What** are the functions of neutrophils and lymphocytes? **How** do these cells differ in function from basophils, eosinophils, and monocytes?
4. **How** do the red blood cells carry oxygen to the tissues?
5. **How** are blood types determined?
6. **How** do platelets initiate blood clotting?
7. **What** are the effects of anemia and blood-borne pathogens on the blood?

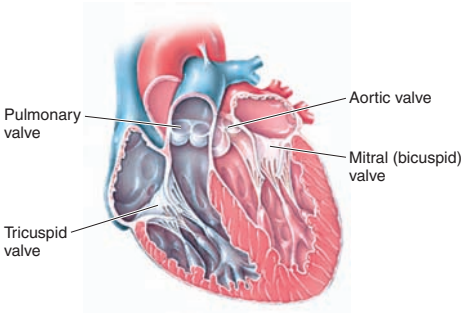
Summary

THE PLANNER

1 The Heart Ensures Continual, 24/7 Nutrient Delivery 310

- The cardiovascular system is responsible for the transport of nutrients, gases, and waste products in the body. It is a closed system, consisting of the heart, arteries, veins, and capillaries. The heart serves as the pump for the cardiovascular system, pushing blood through the body. The heart has four chambers: two atria and two ventricles. The ventricles generate the force needed to move the blood. As shown here, the **bicuspid, tricuspid**, aortic, and pulmonary valves in the heart prevent backflow. Cardiac output is the amount of blood pumped by the heart in one minute. See the figure for blood flow.

Figure 12.4



- The conduction system of the heart consists of the SA node, AV node, AV bundle, bundle branches, and the **Purkinje fibers**. The contraction impulse follows this pathway, ensuring that the heart contracts effectively. The ECG records the changes in electrical charge as the cardiac cells contract. The P wave is the depolarization of the atria, the QRS complex is the depolarization of the ventricles, and the T wave is the repolarization of the ventricles. The time between events measures the speed of transfer of the contraction impulse.

2 Blood Transport Involves Miles of Sophisticated Plumbing 318

- Arteries carry blood from the heart, capillaries are the exchange vessels, and veins return the blood to the heart. The walls of these vessels differ according to the differing pressures they carry.
- Veins, with extremely low-pressure flow, require valves in order to prevent backflow.

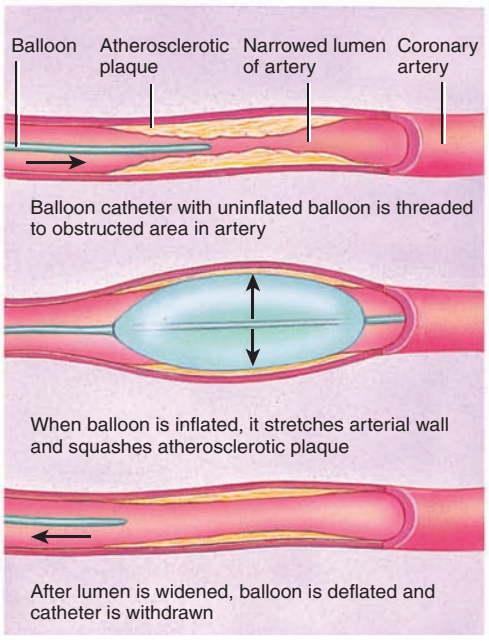
3 Different Circulatory Pathways Have Specific Purposes 321

- Vessels that lead from the heart to the lungs and back to the heart comprise the pulmonary circuit.
- The systemic circuit includes vessels that leave the heart, travel through the tissues, and return to the heart.

4 Cardiovascular Disorders Have Life-Threatening Consequences 322

- Cardiovascular disease is the leading cause of death in the United States. It includes many different problems, such as hypertension, atherosclerosis, heart attack, heart failure, embolism, and stroke. Genetic factors play a role in hypertension, atherosclerosis, heart attack, and heart failure.
- High blood pressure affects body tissues by damaging or destroying capillary beds. Vessels become clogged with fatty deposits in atherosclerosis.
- Heart attack, or myocardial infarction, is due to a lack of blood flow to a region of the heart. Angioplasty (shown here), stent placement, or bypass surgery may correct cardiac atherosclerosis and prevent heart attack.

Figure 12.13

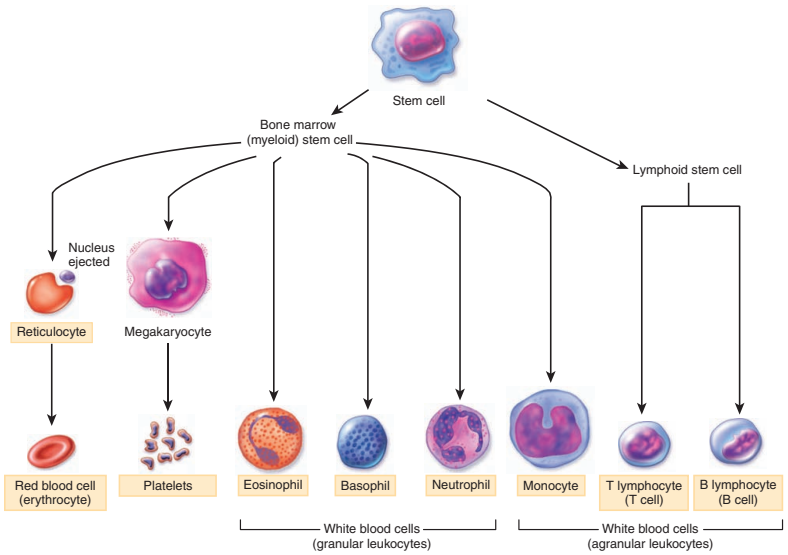


- Heart failure is an inability of the heart to pump blood from the left ventricle through the body.

5 Blood Consists of Plasma and Formed Elements 327

- Blood is a liquid connective tissue composed of plasma, red blood cells, white blood cells, and platelets. The plasma serves to hydrate the body and dissolve nutrients. The red blood cells transport oxygen, using hemoglobin, which drops oxygen in areas of low oxygen concentration and picks it up in areas of high concentration. RBCs carry marker substances on their surface, designating blood as type A, B, AB, or O.
- In addition, there is an Rh factor on most people's RBCs. The ABO blood groups are genetically determined and can be used to trace lineage. Type A blood has anti-B **agglutinins**; Type B blood has anti-A agglutinins; and Type O blood has both agglutinins. Type AB blood has neither agglutinin, because that would harm the individual. Many other blood groups are based on proteins and glycoproteins on the surface of the RBCs.
- White blood cells provide immunity and nonspecific defense. There are five types of white blood cells: neutrophils, lymphocytes, monocytes, eosinophils, and basophils. Each has a specific job and occurs in a specific percentage in a healthy individual.
- Platelets maintain fluid homeostasis. They either form a platelet plug to block the loss of blood in small tears or release factors that initiate clotting. Clot formation is a positive feedback loop, continuing until blood no longer flows past the injured area.
- Anemia is the most common blood disorder. RBC numbers decline, and oxygen-carrying capacity of the blood drops. Causes range from lack of iron in the diet to inadequate protein formation to bleeding and loss of blood volume. Sickle cell anemia is a special type of anemia in which the hemoglobin is incorrectly formed, causing a drop in RBC levels.
- Leukemia is another blood disorder that affects the white blood cells. Causes of leukemia may include exposure to carcinogens and nuclear radiation. Leukemia is treated with chemotherapy or bone marrow transplant surgery.
- Blood can carry a wide range of pathogens. Many are spread by contact with contaminated blood, which is one reason for using caution in sexual activity. Blood banks must test blood for viruses before distributing blood for transfusions. HIV, herpes, and other STDs are examples of blood-borne pathogens.

Figure 12.15



Key Terms

- agglutinin 334
- anastomoses 325
- bicuspid 313
- capillary bed 320
- cardiac sinus 314
- codominant 334
- colony-stimulating factors 329
- congenital 318
- diastole 314
- edema 320
- electrocardiogram 317
- electrolytes 329
- erythrocytes 329
- erythropoiesis 332
- hemolymph 332
- hormones 327
- hypertrophy 314
- invertebrate 332
- ischemia 318
- leukocytes 329
- lumen 319
- mediastinum 311
- prolapse 313
- Purkinje fibers 317
- systole 314
- tachycardia 326
- tricuspid 313
- venules 320

Critical and Creative Thinking Questions

1. Most reptiles and amphibians have a three-chambered heart, with only one ventricle. Blood flows from the lungs and body into this single pumping chamber, which pushes the blood to the body or the lungs. How does this compare with the functioning of the four-chambered heart of mammals? Explain the physiological advantage of separate left and right ventricles.
2. Artificial pacemakers can override the natural heartbeat set by the SA node. These electronic devices set a constant heartbeat that is not sensitive to the body's demands. List some activities that would be challenging for a patient with an artificial pacemaker. What innovations could improve pacemaker technology?
3. Most capillaries are diffusion vessels, meaning that nutrients, oxygen, waste material, and hormones can pass through their walls and into surrounding cells (or vice versa). What features of the structure of a capillary wall raise diffusion capacity—how does structure relate to function in this case? What special modifications would you expect to see in areas where diffusion is prevented, as in capillaries of the brain?
4. Marie was born and raised in Denver, Colorado, the "mile high" city. She has been a cross-country runner since grade school. When Marie went to college in Florida, her running times improved. What might explain this sudden improvement?
5. **CLINICAL CLICK QUESTION**
   Although she had done nothing strenuous all day, 62-year-old Mary felt extremely tired. She found herself unable to complete her usual 1-mile walk with her dog without taking many short rest stops. This loss of stamina prompted her to visit her physician. "Look at my puffy ankles!" she exclaimed, as she sat down in the doctor's office. When her physician took Mary's pulse, it was faster than expected, at 110 beats per minute. Her breathing rate was increased as well, although Mary complained of feeling breathless. Mary's blood pressure was within normal range at 110/70 mmHg. When questioned, she admitted to having trouble sleeping lately unless she sat upright. Mary's medical history included a heart attack (myocardial infarction) just two years ago, with successful treatment through bypass surgery. What organ is not functioning properly for Mary? What questions might you ask of her to help with your diagnosis? Given this brief case, can you make a determination as to what might be going wrong? Specifically what is causing her shortness of breath? Her tiredness? Using the information obtained there, can you prescribe a treatment for Mary? Visit http://www.americanheart.org/presenter.jhtml?identifier=4585 to see whether your diagnosis was correct.

What is happening in this picture?

People living at high altitudes tend to have a cardiovascular system that has adapted to its environment. Hemoglobin concentrations are higher than normal in Peruvian highlanders, for example. Their right ventricles tend to be more developed than those of people living at sea level.

Think Critically

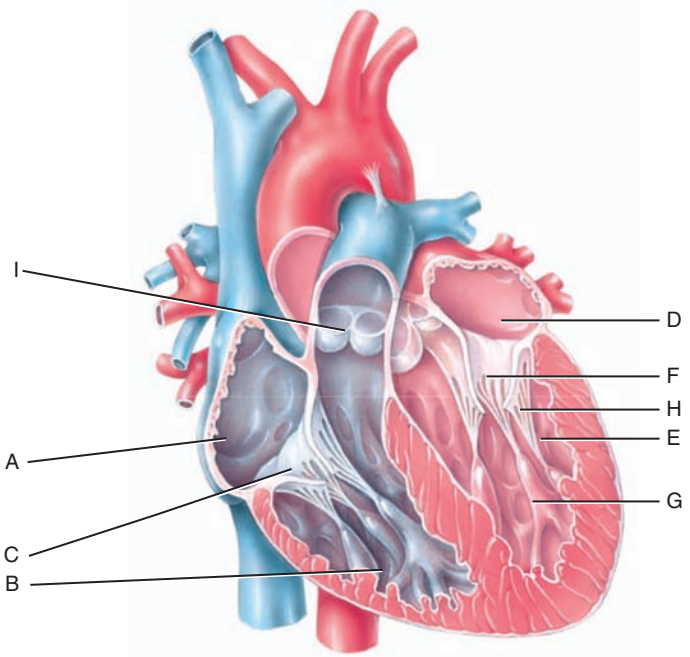
1. What other cardiovascular adaptations do you think the Peruvian highlanders might have?
2. Can you think of any other systems that may function differently in these people, helping them to remain warm and healthy at these colder high altitudes?
3. What adaptations would you expect they might demonstrate in their cutaneous system?
4. In their respiratory system?
5. In their muscular system?

NATIONAL GEOGRAPHIC

Self-Test

1. The correct pattern of blood flow through the cardiovascular system is as follows:
   a. heart → veins → arteries → capillaries → heart
   b. heart → arteries → capillaries → veins → heart
   c. heart → veins → capillaries → arteries → heart
   d. heart → capillaries → veins → arteries → heart

For Questions 2 and 3, refer to the following figure.



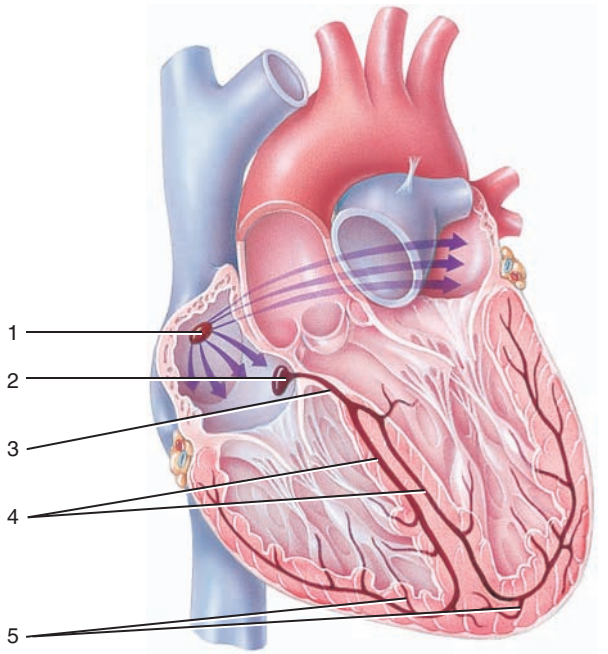
2. The chamber of the heart that receives blood from the lungs is _____.
   a. A
   b. B
   c. D
   d. E

3. The valve that prevents backflow of blood returning from the body is _____.
   a. A
   b. C
   c. F
   d. I

4. When the heart is relaxed, it is said to be in diastole.
   a. True
   b. False

5. During the cardiac cycle, the stage that immediately follows atrial systole is _____.
   a. atrial diastole
   b. ventricular systole
   c. ventricular diastole
   d. whole heart diastole

Use the following figure to answer Questions 6, 7, and 8.



6. The structure that initiates the heartbeat, indicated by the number 1, is the _____.
   a. Purkinje fibers
   b. AV node
   c. bundle branches
   d. SA node

7. The structure responsible for the P wave on an ECG is number _____.
   a. 1
   b. 2
   c. 3
   d. 4

8. Once the heartbeat begins, the function of the structure labeled 2 is to _____.
   a. spread the impulse to contract to the cells of the stria
   b. slow the impulse to contract and pass it to the AV bundle and on to the ventricles
   c. allow the impulse to reach all the cells of the ventricles simultaneously
   d. send the impulse to contract on to the bundle branches

9. The blood vessel that is thin-walled, includes valves, and carries blood under little pressure is the _____.
   a. artery
   b. capillary
   c. vein
   d. All of the above fit this description.

10. The main difference between the pulmonary circuit and the systemic circuit is that in the pulmonary circuit, _____.

a. oxygen-rich blood leaves the heart for the lungs

b. pulmonary veins carry oxygen-poor blood

c. pulmonary arteries carry oxygen-poor blood

d. blood in the pulmonary circuit goes to the brain only

11. When a blood vessel of the leg becomes occluded (blocked) by a fatty deposit, the resulting condition is _____.

a. stroke

b. aneurysm

c. myocardial infarction

d. atherosclerosis

12. Congestive heart failure _____.

a. causes a buildup of fluid in the lungs and pericardium

b. is more common in the elderly than in the young

c. is due to a weakened left ventricle

d. All of the above are correct.

13. The most common cell in the blood is the _____.

a. neutrophil

b. leukocyte

c. erythrocyte

d. platelet

14. Hemoglobin is specialized to _____ oxygen where pH is low, oxygen concentration is low, or temperatures are high.

a. release

b. pick up

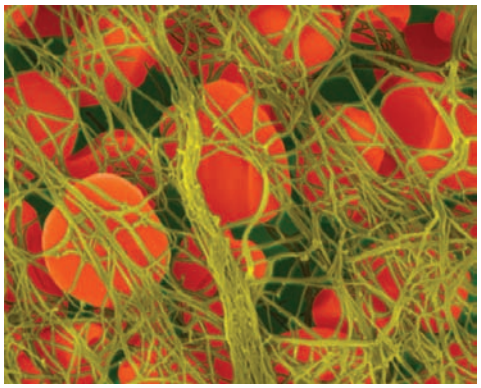
15. The plasma protein that is activated and forms a network of fibers across a wound to trap RBCs is _____.

a. prothrombin

b. thrombin

c. fibrinogen

d. fibrin

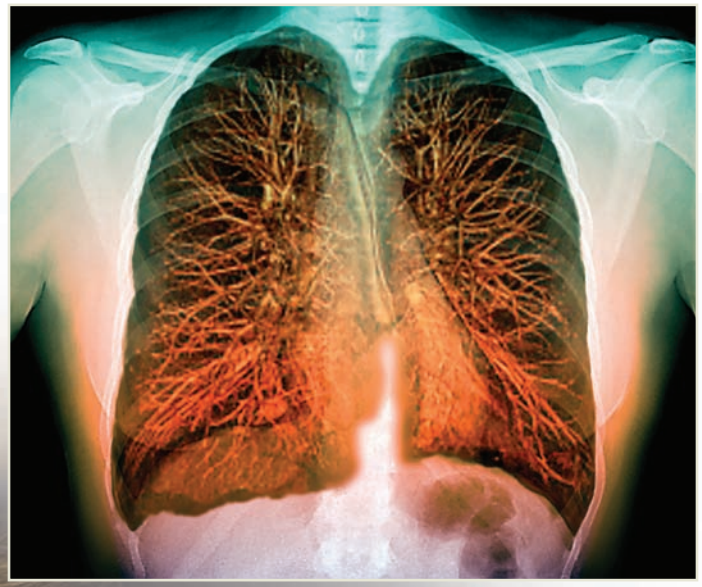


THE PLANNER

Review your Chapter Planner on the chapter opener and check off your completed work.

13 The Respiratory System: Movement of Air

Despite getting a full 8 hours of sleep, you often awaken tired and irritable. Those who share a sleeping area with you tell you that you are a champion snorer, and you realize that must be why you hardly ever feel rested. What is causing that horrid loud noise? Snoring is perhaps the most common sleep disorder in the United States, affecting a good 45% of the population at one time or another. Twenty-five percent of the U.S. population are considered habitual snorers. These are the individuals who suffer from sleep disruptions, and often require medical assistance to get a good night's sleep. Sinus infections, nasal polyps, allergies, or a nasal deformity such as a deviated septum can provoke snoring. These obstructions in the nose prevent air from moving freely, resulting in a vibration of the walls of the throat. Snoring can also be caused by sleeping pills or alcohol, as these chemicals relax the muscles of the throat and tongue to the point where they collapse against the airway, again vibrating with passing air. Even something as seemingly unrelated as being overweight can cause snoring, as overweight individuals often carry an excess of tissue in the throat—tissue that can begin vibrating. Along with being terribly annoying, snoring can lead to serious health issues. Sleep apnea, a temporary stop in breathing while asleep, is a serious problem associated with chronic snoring. Sleep apnea leads to high blood pressure, sequential poor nights' sleep, mental sluggishness, physical fatigue, and higher risks of heart attack and stroke. A good night's sleep is an important part of a healthy lifestyle, and this requires a healthy respiratory system.



CHAPTER OUTLINE

The Respiratory System Provides Us with Essential Gas Exchange 346

- The Upper Respiratory Tract Has an Inspiring Role
- The Lower Respiratory Tract Routes Air to the Lungs
- Gases Are Exchanged in the Respiratory Zone

Air Must Be Moved in and out of the Respiratory System 356

- Inhalation and Exhalation Are Controlled by Muscles
- Your Brain Stem Sets Your Respiratory Rate
- Different Respiratory Volumes Describe Different Types of Breath

External Respiration Brings Supplies for Internal Respiration 360

- External Respiration Secures Oxygen and Disposes of Carbon Dioxide
- Internal Respiration Supplies Oxygen to the Cells and Removes Their Gaseous Waste

Transport of Oxygen and Carbon Dioxide Requires Hemoglobin and Plasma 362

- Hemoglobin Transports Oxygen
- Several Mechanisms Transport Carbon Dioxide

Respiratory Health Is Critical to Survival 365

- Constrictive Diseases Are Serious but Often Sporadic
- Obstructive Diseases Cause Permanent Lung Damage

CHAPTER PLANNER

- ❑ Study the picture and read the opening story.
- ❑ Scan the Learning Objectives in each section:
  p. 346 ❑ p. 356 ❑ p. 360 ❑ p. 362 ❑ p. 365 ❑
- ❑ Read the text and study all figures and visuals. Answer any questions.

Analyze key features

- ❑ Biological InSight, p. 352
- ❑ I Wonder..., p. 355
- ❑ Process Diagram, p. 357 ❑ p. 364 ❑
- ❑ What a Scientist Sees, p. 359
- ❑ Ethics and Issues, p. 368
- ❑ Health, Wellness, and Disease, p. 370
- ❑ Stop: Answer the Concept Checks before you go on:
  p. 356 ❑ p. 360 ❑ p. 362 ❑ p. 364 ❑ p. 370 ❑

End of chapter

- ❑ Review the Summary and Key Terms.
- ❑ Answer the Critical and Creative Thinking Questions.
- ❑ Answer What is happening in this picture?
- ❑ Answer the Self-Test Questions.

13.1 The Respiratory System Provides Us with Essential Gas Exchange

LEARNING OBJECTIVES

1. **Explore** the overall function of the respiratory system.
2. **Identify** the structures of the upper and lower respiratory tracts.
3. **Differentiate** the conducting zone from the respiratory zone.
4. **Discuss** the anatomy and physiology of the alveolar sac.

Thus far in our treatment of survival, we have talked about protecting ourselves from the environment, moving through the environment, and sensing and reacting to external and internal changes. We explored how the cardiovascular system (Chapter 12) moves nutrients, gases, and waste through the body. Now it is time to discuss how the cardiovascular system cooperates with the respiratory system, which delivers oxygen and expels carbon dioxide. The respiratory system also filters incoming air, maintains blood pH, helps control fluid and thermal homeostasis, and produces sound. Otherwise, speech (and biology lectures!) would be impossible.

upper respiratory tract Respiratory organs in the face and neck.

lower respiratory tract Respiratory organs within the thoracic cavity, including the bronchial tree and the lungs.

The respiratory system has two anatomical divisions, the **upper respiratory tract** and the **lower respiratory tract**, with separate but related functions—see Figure 13.1. The upper tract conditions air as it enters the body, and the lower tract allows oxygen to enter the blood and waste gases to leave it.

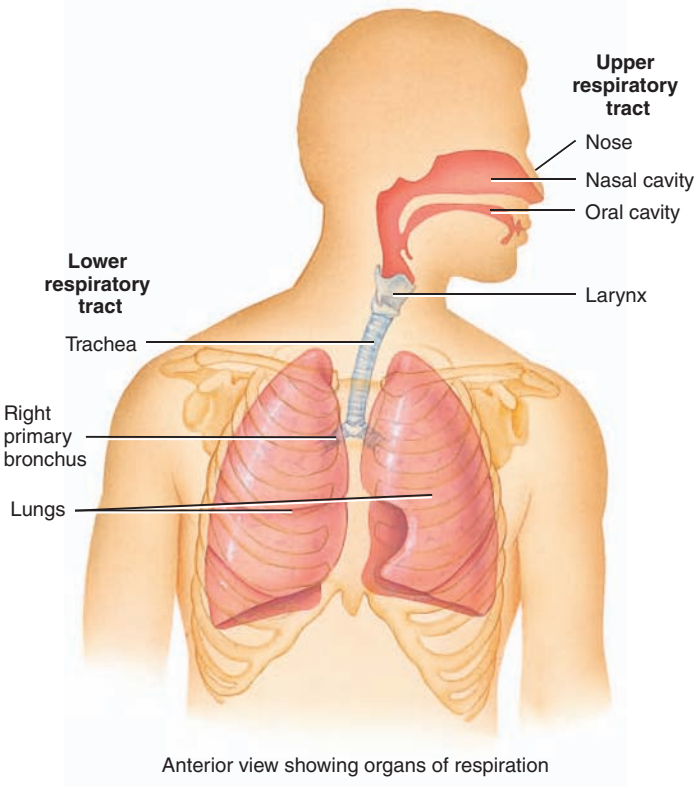
The Upper Respiratory Tract Has an Inspiring Role

The structures of the upper respiratory tract—the **nose**, **pharynx**, and **larynx**—warm, moisten, and filter the incoming air, as shown in Figure 13.2. The nose is one of the first body parts that small children can identify. We are familiar with the external portion of the nose, consisting of the nasal bone and hyaline cartilage, covered by skin and muscle. The division between the two nostrils, or **external nares**, is a plate of hyaline cartilage called the **septum**. The septum is attached to the vomer bone at its base. Both the septum and the cartilages that make up the sides of the nose serve to support the nasal openings. If a blow to the nose moves these cartilages to the side of the vomer, airflow is blocked. To treat this "deviated septum," surgeons restore the septum into position and open both nasal passageways. Surgery on the nose (called **rhinoplasty)** can also be done for cosmetic reasons, usually by breaking the nasal bone and reshaping the nasal cartilages.

pharynx Throat.

larynx Voice box (Adam's apple).

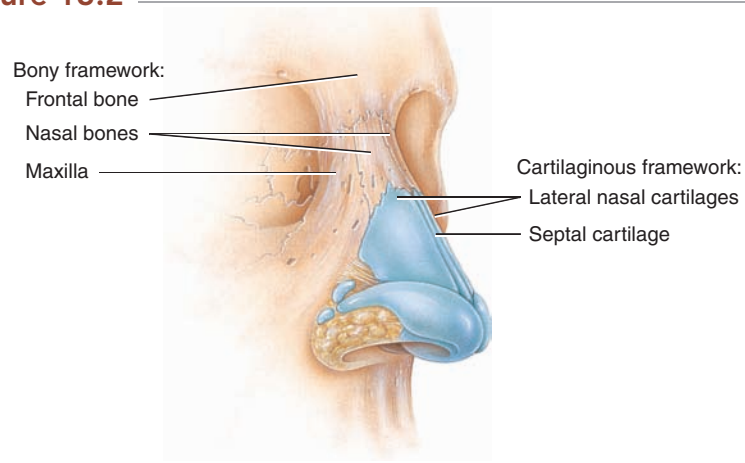
Respiratory tract anatomy • Figure 13.1



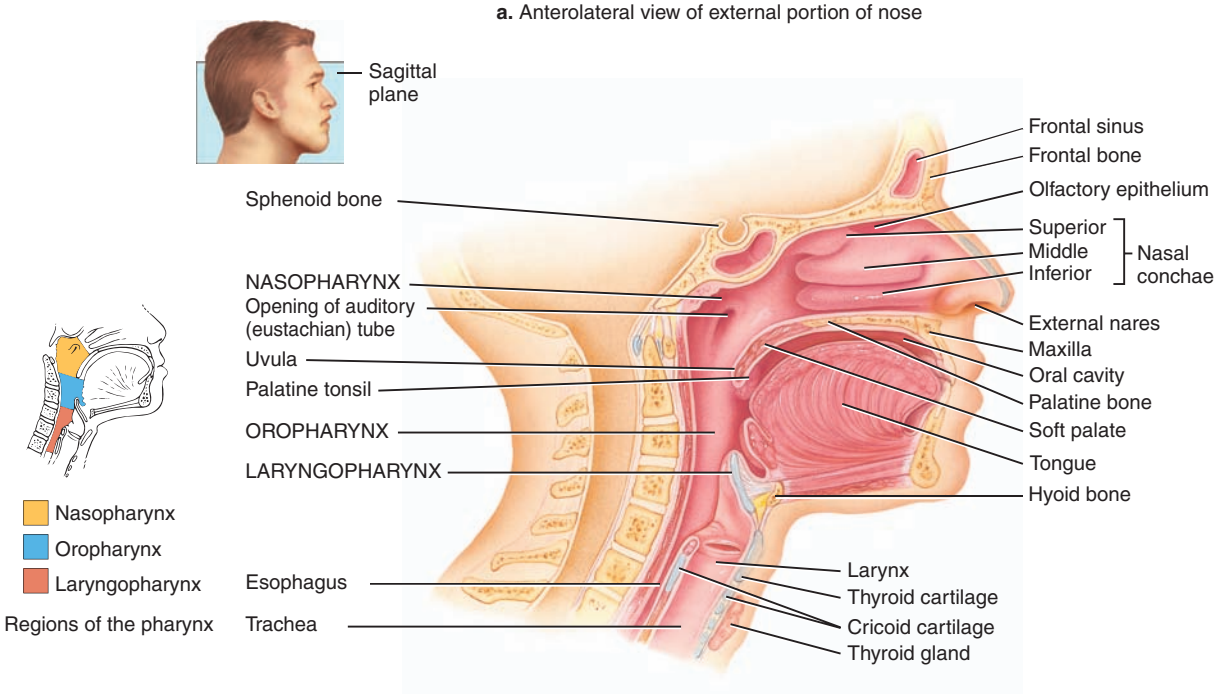
Anterior view showing organs of respiration

Upper respiratory tract • Figure 13.2

The convoluted nasal conchae swirl the incoming air, which is moistened and heated by mucous membranes before the air is sent to the lower respiratory tract.



a. Anterolateral view of external portion of nose



b. Sagittal section of the left side of the head and neck showing the location of respiratory structures

The nose has many functions. As mentioned, the nasal cavity warms, filters, and moistens incoming air, and does so far better than the mucous membranes of the mouth. Swirls and ridges in the nasal cavity slow the air. As inhaled air moves through this convoluted space, it contacts the nasal epithelium. The epithelium in the nasal conchae and nasopharynx is **pseudostratified ciliated columnar** epithelium. In the nasal region, this tissue is covered in mucus and constantly washed by tears draining from the eyes.

A large blood supply warms the nasal epithelium, and both the warmth and moisture are transferred to the inhaled air. If you have ever bumped your nose, you know of this large blood supply. Most of us have had a bloody nose at least once, and were surprised by the remarkable quantity of blood that leaked out.

Filtering is a vital function of the nose because inhaled particles would seriously inhibit airflow in the lower respiratory tract. Coarse hairs in the nostrils filter out larger particles, and the mucus of the nasal passages further filters incoming air by trapping small particles.

A final function of the nasal epithelium is the sense of smell (as described in Chapter 8). To smell something more clearly, we often inhale deeply to ensure that airborne compounds reach the patch of nasal epithelium that is studded with chemosensory neurons.

The pharynx has three parts. The **internal nares**, the twin openings at the back of the nasal passageway, lead to the **nasopharynx**, or upper throat. The passageway between the nose and throat is normally open for breathing, but it must close when we swallow. The **uvula**, a fleshy tab of tissue that hangs down in the back of the throat, contracts when touched by solids, moving upward and closing the internal nares. When your doctor asks you to say "Ahh" during a throat examination, you contract the uvula and move it up so the doctor can see the nasopharynx and the tonsils on the posterior wall of the pharynx. If you laugh or cough while drinking, the uvula may spasm, and liquids may leak past it. These liquids may be forced out the external nares, causing a burning sensation as they travel the nasal passages—and some slight embarrassment.

The eustachian, or auditory, tubes link the nasopharynx and the middle ear. When your ears "pop," these tubes open to equalize air pressure between the middle and outer ear.

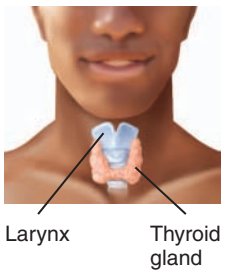
The **oropharynx**, the area directly behind the tongue, is covered by the uvula when it hangs down. This portion of the throat is devoted to activities of the mouth. Food and drink pass through the oropharynx with each swallow, so the mucous membrane and epithelium lining this region are usually thicker and more durable than elsewhere in the pharynx. The palatine and lingual tonsils are found in the oropharynx as well.

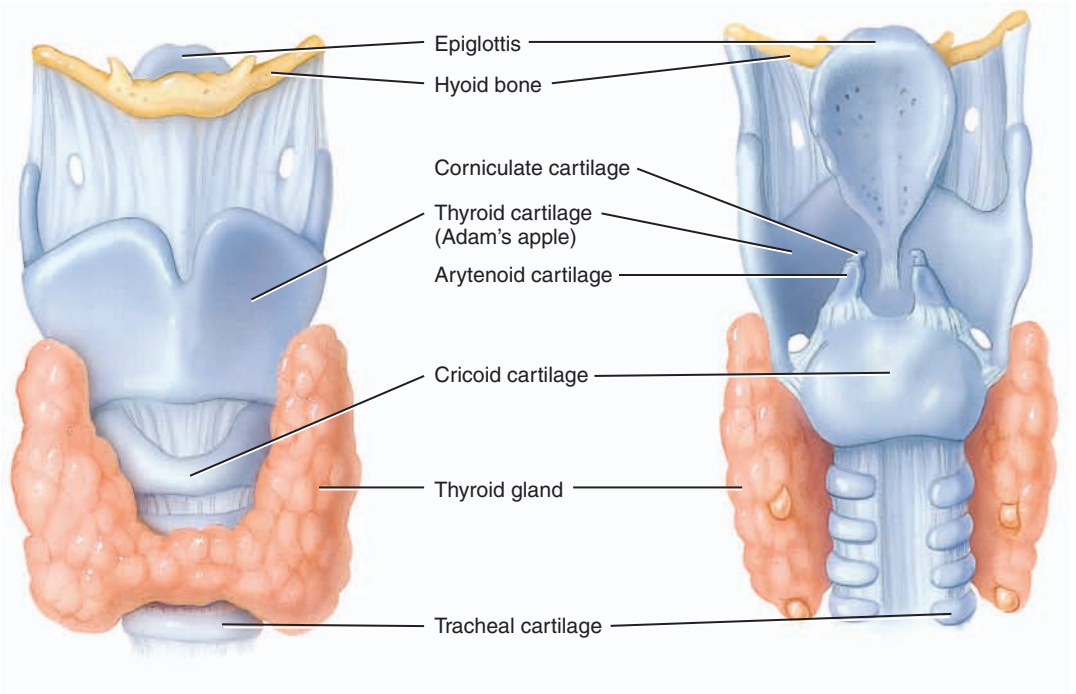
The lowest level of the pharynx, called the **laryngopharynx**, is the last part of the respiratory tract shared by the digestive and respiratory systems. The end of the laryngopharynx has two openings. The anterior opening leads to the larynx and the rest of the respiratory system. The posterior opening leads to the esophagus and the digestive system.

The larynx divides the upper and lower respiratory tracts. The larynx is composed entirely of cartilage and has several functions. It holds the respiratory tract open, guards the lower tract against particulate matter, and produces the sounds of speech. The larynx is composed of nine pieces of hyaline cartilage: three single structures and three paired structures. The single pieces are the **thyroid cartilage**, the **epiglottis**, and the **cricoid cartilage**, as shown in Figure 13.3.

The **thyroid cartilage** lies in the front of the larynx. It is shield-shaped and often protrudes from the throat. Because males produce more testosterone than females, and testosterone stimulates cartilage growth, the thyroid cartilage in men is usually larger than in women. One common name for the larynx, "Adam's apple," refers to the larger laryngeal cartilages in men.

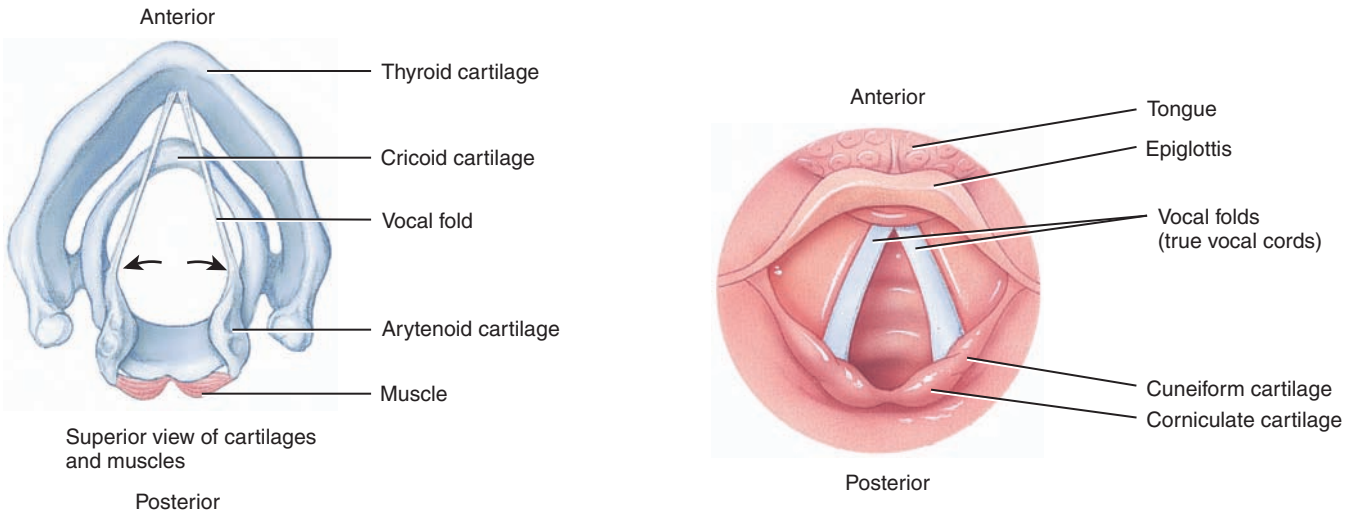
Larynx • Figure 13.3





a. Anterior view **b.** Posterior view

Vocal folds • Figure 13.4



a. Movement of vocal folds apart (abduction)

b. View through a laryngoscope

The **epiglottis** covers the opening to the lower respiratory tract to prevent food from entering (*epi* means "on top of" and *glottis* means "hole"). The epiglottis is a leaflike flap of cartilage on the superior (upper) aspect of the larynx, covering the hole leading to the lungs. A pair of small **corniculate cartilages** hold the epiglottis in position above the glottis. The larynx is attached to the tongue muscles. When the tongue pushes against the roof of the mouth in preparation for swallowing, the larynx moves up toward the epiglottis. Food particles hitting the top of the epiglottis complete the closure by causing the epiglottis to rest against the top of the larynx. You can feel this movement by touching your "Adam's apple" and swallowing. You will feel the entire larynx move up with your tongue.

The **cricoid cartilage** is the only complete ring of cartilage in the respiratory system. It is narrow in front but thick in the back of the larynx. The cricoid cartilage holds the respiratory system open. If it is crushed, airflow is impeded and breathing becomes nearly impossible. In an emergency, it may be necessary to surgically open the airway below a crushed cricoid cartilage.

The larynx is called the "voice box" because it is the location of the vocal cords. As seen in **Figure 13.4**, you have two pairs of vocal cords: false vocal cords, or ventricular folds, and true vocal cords, or **vocal folds**. The vocal folds are covered by mucous membrane and held in place by elastic ligaments stretched across the glottis. These folds vibrate as air moves past them, producing sound. High-pitched sounds occur when tension on the vocal folds increases, and low-pitched sounds occur when the tension is reduced. We unconsciously adjust tension on the vocal folds by moving the paired laryngeal cartilages. The **arytenoid** and **cuneiform cartilages** pull on the vocal folds to alter pitch. The amplitude, or amount the cords are vibrating, determines sound volume.

vocal folds A pair of cartilaginous cords stretching across the laryngeal opening that produce the tone and pitch of the voice.

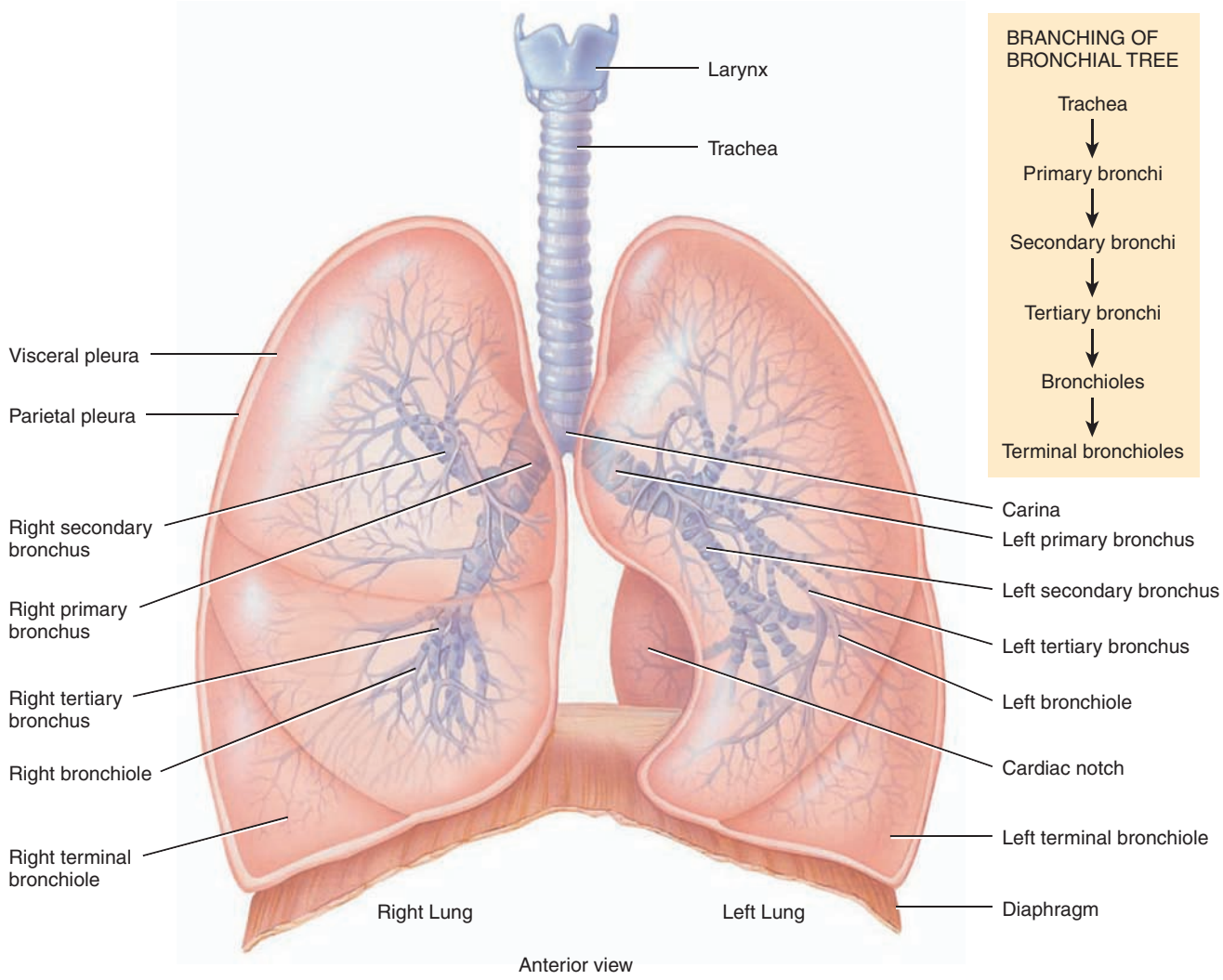
As boys reach puberty and their testes produce more testosterone, their voices change. Testosterone stimulates the growth of cartilage in the larynx, thickening the vocal folds. Boys train their voices through daily use to adjust their vocal fold tension based on the size of the larynx. As the larynx grows, the tension needed to produce the same sounds changes. In effect, the young male must retrain his voice to maintain vocal tone. When the larynx is growing quickly, the male's voice will often "crack" or "squeak" due to his inability to adjust the tension on his changing vocal folds.

The Lower Respiratory Tract Routes Air to the Lungs

The main function of the lower tract is to move inhaled air to the **respiratory membrane**. Physiologically, the upper tract and the first portion of the lower tract make up the **conducting zone** of the respiratory system, which conducts air from the atmosphere to the **respiratory zone** deeper

respiratory membrane The thin, membranous "end" of the respiratory system where gases are exchanged.

The lower respiratory tract • Figure 13.5



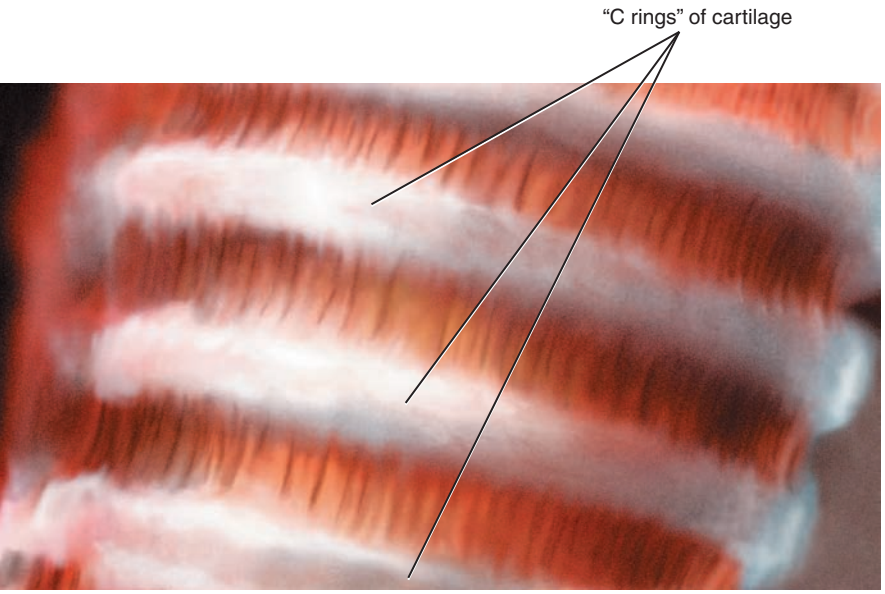
in the body, where the actual exchange of gases takes place. The conducting zone includes all the structures of the upper respiratory tract, as well as the **trachea, bronchi, bronchioles**, and **terminal bronchioles**. The respiratory zone lies deep within the lungs and includes only the **respiratory bronchioles** and the **alveoli**. See Figure 13.5. The lower portion of the conducting zone and the respiratory zone are collectively referred to as the bronchial tree.

The trachea connects the larynx to the bronchi.

Beyond the larynx, air enters the trachea, a 12-centimeter tube extending from the base of the larynx to the fifth thoracic vertebra—see Figure 13.6. The trachea is approximately 2.5 cm in diameter, and is composed of muscular walls embedded with 16 to 20 C-shaped pieces of hyaline cartilage. (Remember that the cricoid cartilage of the larynx is the only complete ring of cartilage in the respiratory system.) The opening of each "C" is oriented toward the back. You can easily feel the tracheal rings through the skin of your throat, immediately below your larynx.

These cartilage C rings support the trachea so it does not collapse during breathing, and they also allow the esophagus to expand during swallowing. When you swallow a large mouthful of food, the esophagus pushes into the lumen of the trachea as the mouthful passes. If the tracheal cartilages were circular, the food would push the entire trachea forward. Since the trachea is attached to the bronchi of the lungs, this would also move the lungs upward in the thoracic cavity—a structural nightmare! The C-shaped cartilage allows the back of the trachea to compress, so the lungs can remain in the thoracic cavity and the trachea can get the support it needs to remain open.

Trachea • Figure 13.6



In advanced first-aid classes, you learn to locate these rings and identify a position between two rings. You can save someone with a crushed larynx from suffocating by opening the trachea between C rings and inserting a temporary breathing tube so air can flow to the lungs, bypassing the crushed larynx. This is called a **tracheotomy**. Another way to restore breathing is to **intubate**—to insert a tube through the mouth or nose, through the larynx and into the trachea. The tube pushes obstructions aside and/or helps suction them out.

At the lower base of the trachea is an extremely sensitive area called the **carina**. The mucous membrane of the carina is more sensitive to touch than any other area of the larynx or trachea, so this spot triggers a dramatic cough reflex when any solid object touches it.

The trachea splits into the primary bronchi. At the level of the fifth thoracic vertebra, the trachea splits into two tubes called the **primary bronchi**, which lead to each lung. Despite their common function, the two bronchi are slightly different. The right primary bronchus is shorter, wider, and more vertical than the left. For this reason, inhaled objects often get lodged in the right primary bronchus. These two bronchi are constructed very much like the trachea and are held open with incomplete rings of cartilage in their walls.

Inside the lungs, the primary bronchi divide into the **secondary bronchi**. The right bronchus divides into three secondary bronchi, whereas the left splits into two. This branching pattern continues getting smaller and smaller as the tubes extend farther from the primary bronchus. The sequentially smaller tubes are called **tertiary bronchi**, **bronchioles**, **terminal bronchioles**, and **respiratory bronchioles**. The respiratory system looks like an upside-down tree, with the base at the nasal passages and the tiniest branches leading to the "leaves" deep within the lungs.

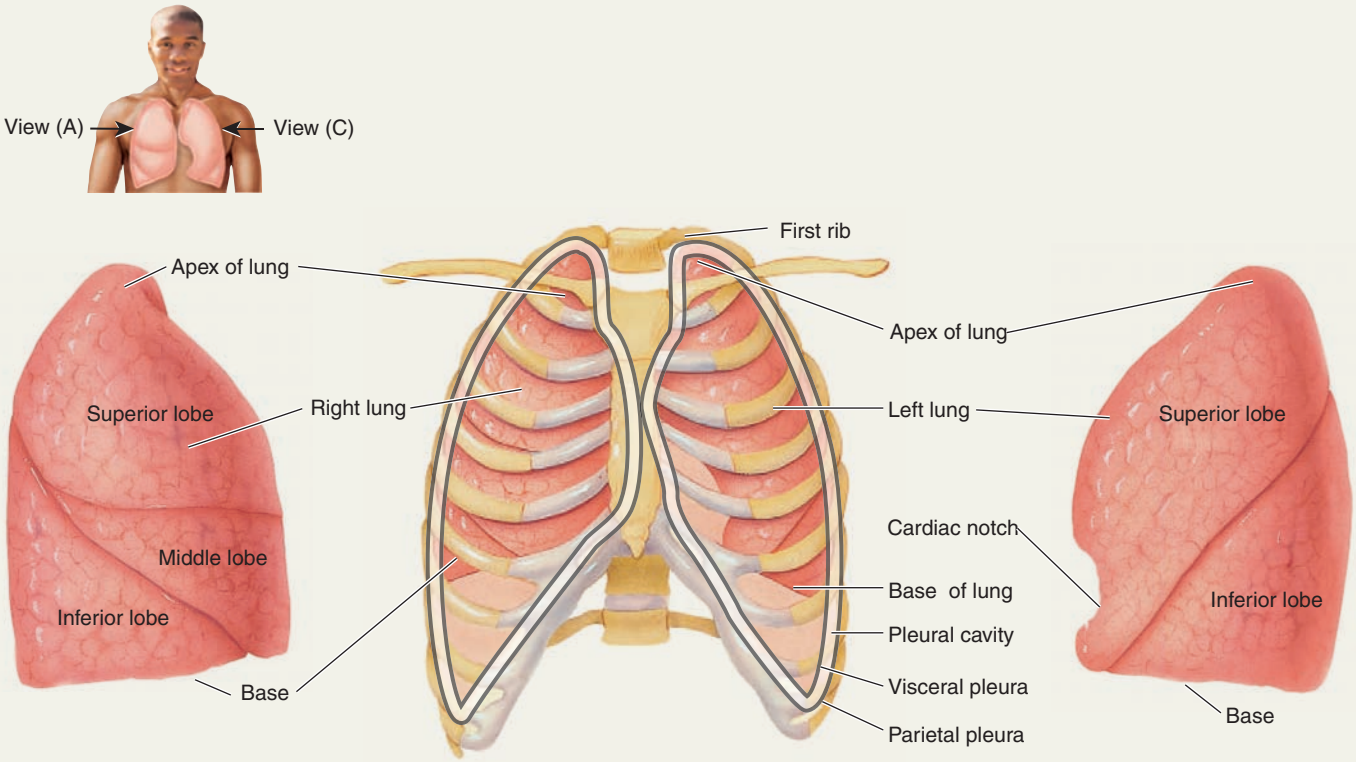
The bronchial tree undergoes two major changes as it reaches deeper into the body:

1. The cells of the mucous membrane get smaller. The epithelium of the upper and beginning portion of the lower respiratory tract is pseudostratified ciliated columnar epithelium. These fairly large cells secrete mucus, which the cilia sweeps upward and outward with any inhaled particles. The epithelium changes to the slightly thinner, ciliated columnar epithelium in the larger bronchioles. The smaller bronchioles are lined with smaller ciliated cuboidal epithelium. Terminal bronchioles have no cilia and are lined with simple columnar epithelium. If dust reaches all the way to the terminal bronchioles, it can be removed only by **macrophages**.

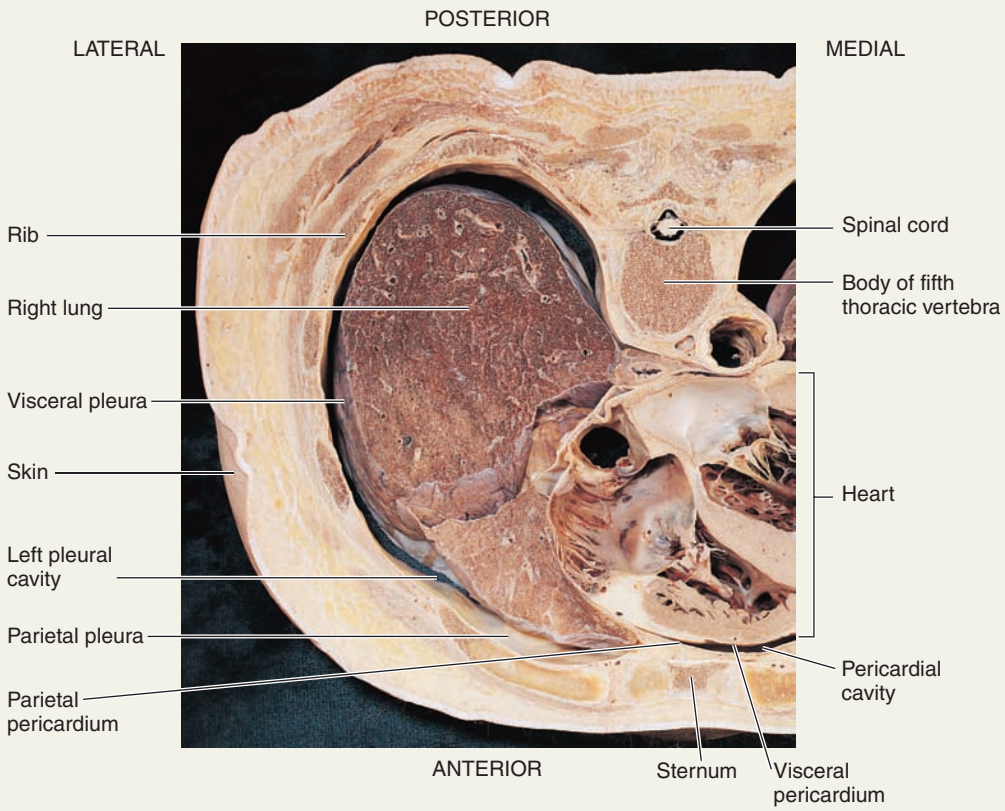
   macrophage Large, phagocytic immune cell that patrols tissue, ingesting foreign material and stimulating immune cells.

2. The composition of the walls of the bronchi and bronchioles changes. Smaller tubes need less cartilage to hold them open, so the incomplete rings of cartilage supporting the bronchi are gradually replaced by plates of cartilage in the bronchioles. These plates diminish in the smaller bronchioles, until the walls of the terminal bronchioles have virtually no cartilage. As cartilage decreases, the percentage of smooth muscle increases. Without cartilage, these small tubes can be completely shut by contraction of this smooth muscle. In asthma and other constrictive respiratory disorders, this smooth muscle becomes irritated and tightens, reducing the tube diameter, sometimes even effectively closing it.

Epinephrine, a hormone that is released into the bloodstream when we exercise or feel fright, relaxes smooth muscle. In the lungs, epinephrine relaxes the smooth muscle of the terminal bronchioles, enlarging the lumen and allowing greater airflow. This greater airflow in turn increases the oxygen content of the blood and allows the muscles to work more efficiently. Someone you know



a. Lateral view of right lung **b.** Anterior view of lungs and pleurae in thorax **c.** Lateral view of left lung



Inferior view of a transverse section through the thoracic cavity showing the pleural cavity and pleural membranes

who has asthma probably carries an "inhaler" filled with "rescue medication." If you get a look at the label, you will probably see that the active ingredient is epinephrine, norepinephrine, or a derivative, such as albuterol. Spraying these drugs on the walls of the bronchioles immediately relaxes the smooth muscle, dramatically increasing tubule diameter.

The lungs are the key organs of respiration. The thoracic cavity houses the two organs of respiration, the **lungs**. See Figure 13.7. These lightweight organs extend from just above the clavicle to the twelfth thoracic vertebra and fill the rib cage. The base of the lungs is the broad portion sitting on the diaphragm. The apex is the small point extending above the clavicles.

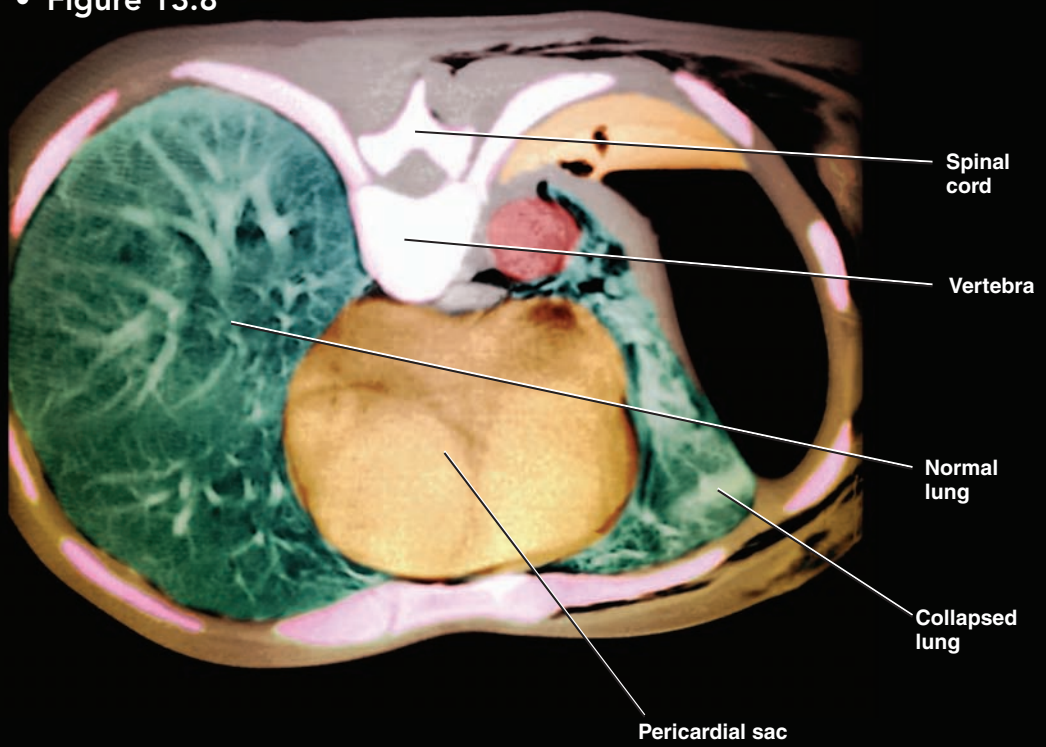
Although the lungs are paired, they are not identical. The right lung is shorter and fatter, and it has three lobes, whereas the left lung has only two lobes. The left lung is thinner and has a depression for the heart, called the cardiac notch, on the medial side. The central portion of the thoracic cavity is called the **mediastinum**; therefore, the medial portion of the lungs is the mediastinal surface. On this surface lies the **hilum** of the lung. Entering and exiting the lung at the hilum are the bronchi, along with the major blood vessels, lymphatics, and nerve supply for the organ.

hilum Site of entry and exit for the nerves, blood vessels, and lymphatic vessels on most organs.

The pleura wraps the lungs. The lungs are covered in a serous membrane called the **pleura** that allows the lungs to expand and contract without tearing the delicate respiratory tissues. The pleura is anatomically similar to the pericardium around the heart in that they are both composed of two membranous layers separated by serous fluid. The **visceral pleura** is snug against the lung tissue, and the **parietal pleura** lines the walls of the thoracic cavity. The **pleural cavity** between the two pleural membranes contains serous fluid. The surface tension of the fluid between these two membranes creates a slight outward pull on the lung tissue. Have you noticed that a thin layer of water on a glass table holds other glass objects to it? In the lungs, this same phenomenon causes adhesion between the visceral and parietal pleura. There is also a slight vacuum in the pleural space, created during development of the lungs and thoracic cavity. This vacuum is essential to proper lung functioning.

If the partial vacuum within the pleural space is lost, inhalation becomes difficult. This can happen if the thoracic cavity is punctured through injury or accident, causing either a **pneumothorax** (air in the pleural space) or a **hemothorax** (blood in the pleural space). If enough air or blood enters the pleural space, lung tissue in that area can collapse, as seen in Figure 13.8. The air or blood must be evacuated and pleural integrity restored, to reinflate the lung and reestablish normal breathing.

Collapsed lung • Figure 13.8



pleurisy Inflammation of the covering surrounding the lungs (the pleura), causing painful breathing.

Pleurisy is less devastating and more common than a collapsed lung. In pleurisy, the pleural membranes swell after being inflamed or irritated, and they rub against each other. Every breath is painful, and deep breathing, coughing, or laughing may be excruciating. Anti-inflammatory drugs can reduce these symptoms.

The **lobes** of each lung are separate sections of the lung that can be lifted away from the other lobes, just as a butcher might separate lobes of beef liver. Air enters each lobe through one secondary bronchus. Despite having different numbers of secondary bronchi, each lung has ten terminal bronchioles, each supplying one **bronchopulmonary segment**.

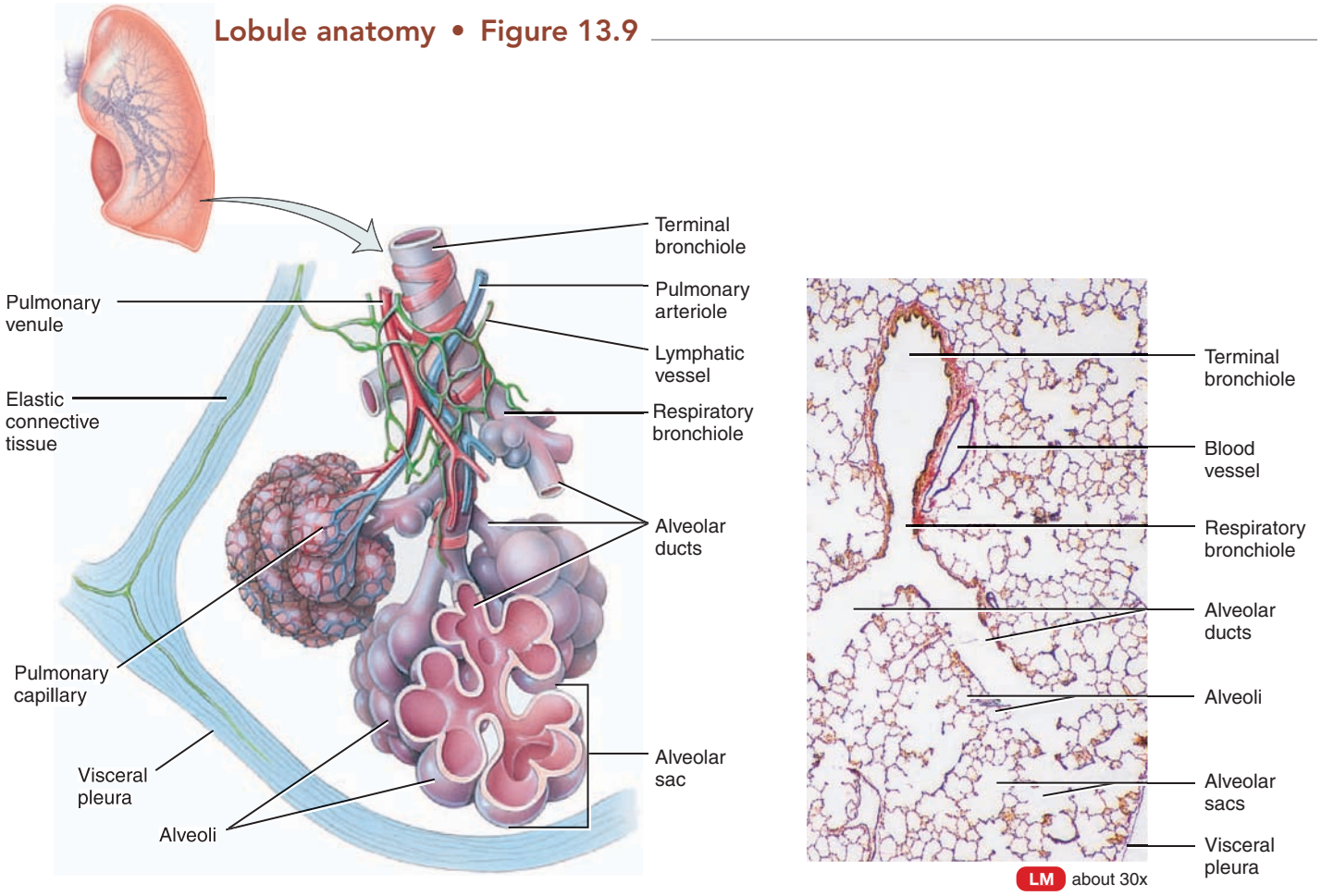
Gases Are Exchanged in the Respiratory Zone

A bronchopulmonary segment looks somewhat like a bunch of grapes on a vine, as shown in Figure 13.9. One terminal bronchiole feeds all the respiratory membranes of each bronchopulmonary segment. One pulmonary arteriole runs to each segment, and one pulmonary venule returns from it. Small groups of respiratory membranes, called lobules, extend off the terminal bronchiole. These lobules are wrapped in elastic tissue and covered in pulmonary capillaries. Lobules are attached to the terminal bronchiole by a respiratory bronchiole.

The respiratory bronchiole leads to alveolar ducts, which finally conduct air to the alveoli, the respiratory membranes for the entire system. At the respiratory membrane, we have finally moved from the conducting zone to the respiratory zone. It is only here, in the alveoli, after traveling through the entire set of tubes in the conducting zone, that gases can diffuse. It is here, and here alone, that oxygen enters the bloodstream and carbon dioxide exits.

The **alveolus** is a cup-shaped membrane at the end of the terminal bronchiole. Alveoli are clustered into an **alveolar sac** at the end of the terminal bronchiole. The key to respiration is diffusion of gases, and diffusion requires extremely thin membranes. The walls of the alveolar sac are a mere two **squamous epithelial**

Lobule anatomy • Figure 13.9

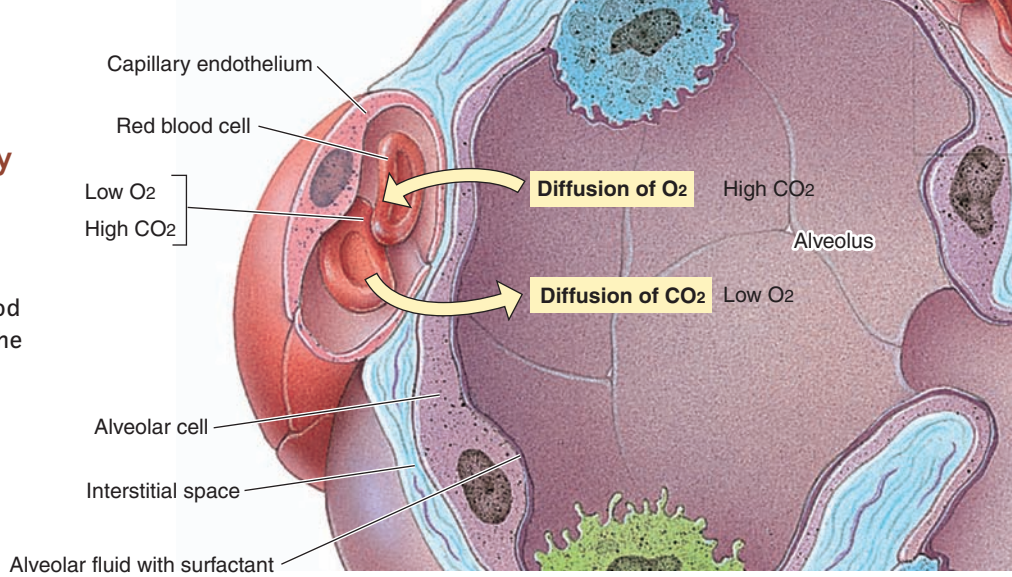


a. Diagram of a portion of a lobule of the lung

b. Lung lobule

Gas movement across the respiratory membrane • Figure 13.10

The arrows in this diagram demonstrate the movement of gases across the respiratory membrane. Oxygen diffuses from the alveoli to the blood in the capillary, while carbon dioxide diffuses in the opposite direction.



cells thick—one cell from the alveolar wall and one from the capillary wall. See **Figure 13.10**. Many things can impede airflow to the respiratory membranes, including asthma and even fungal growth. To understand how that might be, see *I Wonder… Can I Really Get Sick from Breathing Deeply in Caves?*

Diffusion of gases across the cell membrane requires a moist membrane, but moist membranes have a tendency to stick together much like plastic food wrap. **Septal cells**, scattered through the lung, produce **surfactant**, a detergent-like fluid that moistens the alveoli but prevents the walls from sticking together during exhalation. (Imagine how a thin layer of watery detergent would release the bonding of a ball of plastic wrap.) The surfactant also serves as a biological detergent, solubilizing oxygen gas to promote uptake.

WILEY PLUS Video

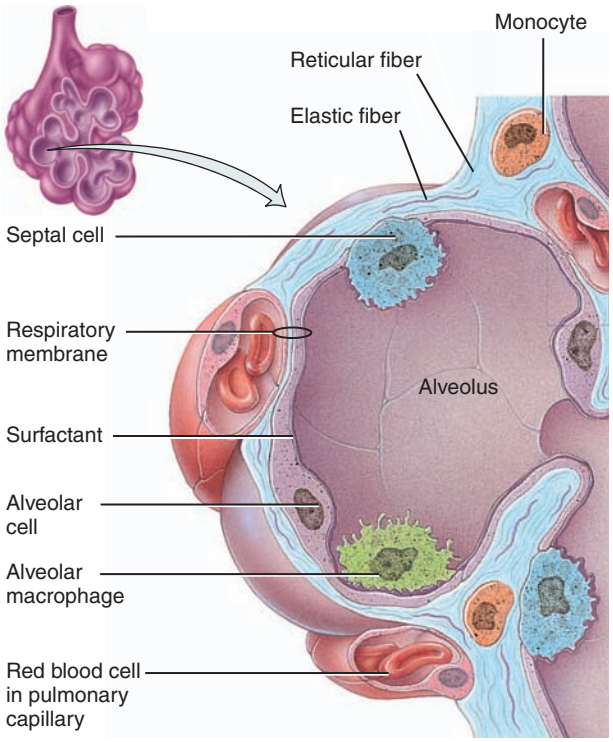
I WONDER...

Can I Really Get Sick from Breathing Deeply in Caves?

Although exploring caves is thrilling, there are dangers to spending time underground, such as getting lost or being trapped by tunnel collapse. Cave exploration can also cause respiratory troubles. The air that is found in caves does not circulate as often as air above. The air can become "stale," carrying less oxygen than normal, and it can also carry poisonous gases. Methane gas may be released into caves from underground pockets. Colorless and odorless, methane kills those unfortunate enough to breath it in large quantities. Miners used canaries to "test" the air. If the canary, with its smaller body size and higher respiratory rate, died, the miners knew that the air quality was diminished. When the canary died, the miners evacuated.

When spelunking, you also run the risk of contracting histoplasmosis. Histoplasmosis is a fungal disease caused by breathing in the spores of the fungus *Histoplasma capsulatum*. It normally grows in soil, and thrives in the enriched soil created by bird or bat droppings. Disturbing infected soil, working in a poultry house, spending time in caves, or cleaning out areas where bats live may cause the spores of this fungus to enter the air. Once in the air, the spores are pulled into the lungs with a normal breath. Within 17 days of exposure, symptoms of histoplasmosis may appear. Symptoms include a general ill feeling, a fever, chest pains, and a dry cough. A chest X-ray confirms the presence of *H. capsulatum* in the alveoli. The good news is that once the fungus settles in lungs, it cannot be spread from one person to another. Breathing in recently disturbed spores is the only way to contract histoplasmosis. Treatment is often not necessary, but in severe cases antifungal medications are effective.

Anatomy of an alveolar sac • Figure 13.11



Section through an alveolus showing its cellular components

The respiratory membrane, at the end of the respiratory tree, consists of alveolar cells, an epithelial basement membrane, the capillary basement membrane, and the endothelium of the capillary.

Because septal cells begin secreting surfactant only during the last few weeks of pregnancy, **premature babies** often have difficulty breathing. Every inhalation requires a gasp to reinflate the collapsed alveoli because their walls stick together. In the late 1980s, artificial surfactant was first administered to premature infants and is now routinely given to them during their first week of life.

Alveolar macrophages, or **dust cells**, patrol the alveoli, as seen in Figure 13.11. These immune cells remove any inhaled particles that escape the mucus and cilia of the conducting zone.

CONCEPT CHECK STOP

1. **What** are the main functions of the respiratory system? **What** are the minor functions of this system?
2. **What** structure marks the break point between the upper and lower respiratory systems? **What** is the function of the structures of the upper respiratory system?
3. **How** are the conducting zone and the respiratory zone different?
4. **How** does the structure of the alveolar sac relate directly to its function?

13.2 Air Must Be Moved in and out of the Respiratory System

LEARNING OBJECTIVES

1. **Explain** inhalation and exhalation in terms of muscle activity.
2. **Understand** how breathing rate is set.
3. **Describe** the various lung volumes, and explain their relationship.

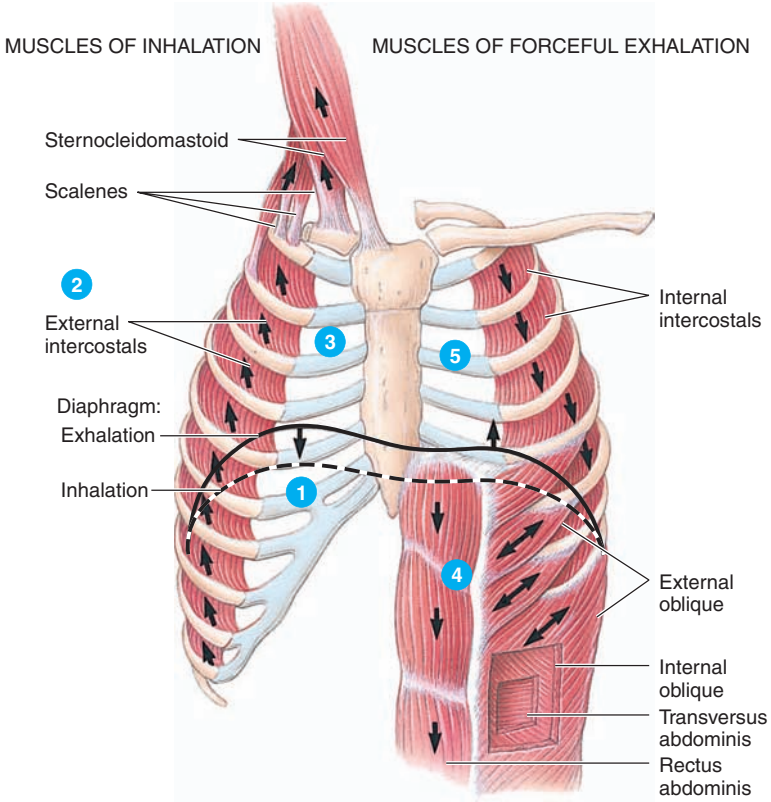
The anatomy of the respiratory system eases the exchange of gases between the air and the body. External air is brought into the depths of the respiratory system during inhalation—but how does this happen? Inhalation (and the opposite movement, called exhalation) is governed by muscular movements of the thoracic cavity. Inhalation is an active process that requires muscle contractions, but exhalation requires only that those muscles relax. The combined inflow and outflow of air between atmosphere and alveoli is called pulmonary ventilation. Pulmonary ventilation is governed by Boyle's law, which states that the volume of a gas varies inversely with its pressure. In other words, if you increase the size of a container of gas without adding gas molecules, the pressure must decrease.

Inhalation and Exhalation Are Controlled by Muscles

When you inhale, your muscles expand your thoracic cavity, as shown in **Figure 13.12**. When your diaphragm contracts it flattens out, causing the bottom of the thoracic cavity to drop. This dropping of the diaphragm causes most of the size increase in the thoracic cavity during an inhalation. The intercostal muscles also contract, raising the ribs slightly. (You can feel this by holding your sides as you breathe and feeling your ribs expand and contract.) The lungs connect to the walls of the thoracic cavity through the pleura, so the lungs must follow the moving walls of

THE PLANNER

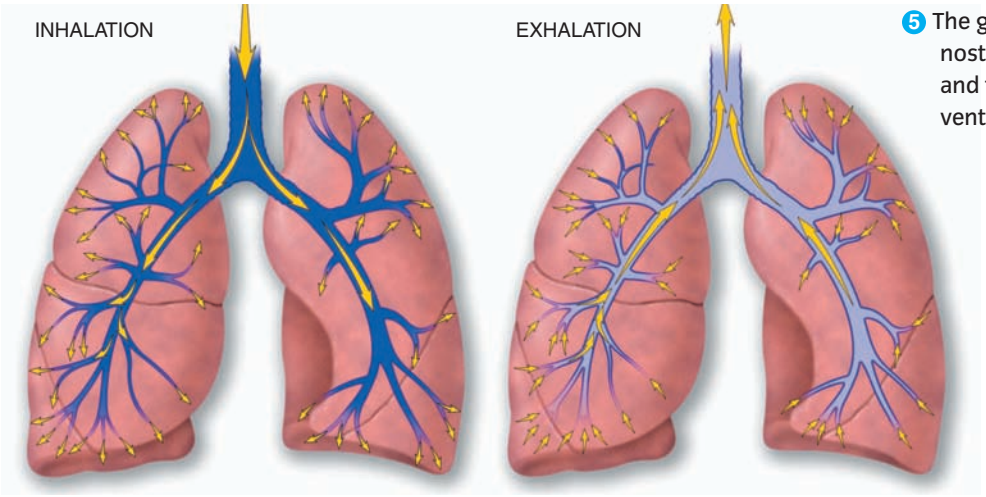
Inhalation: The diaphragm drops and volume increases • Figure 13.12



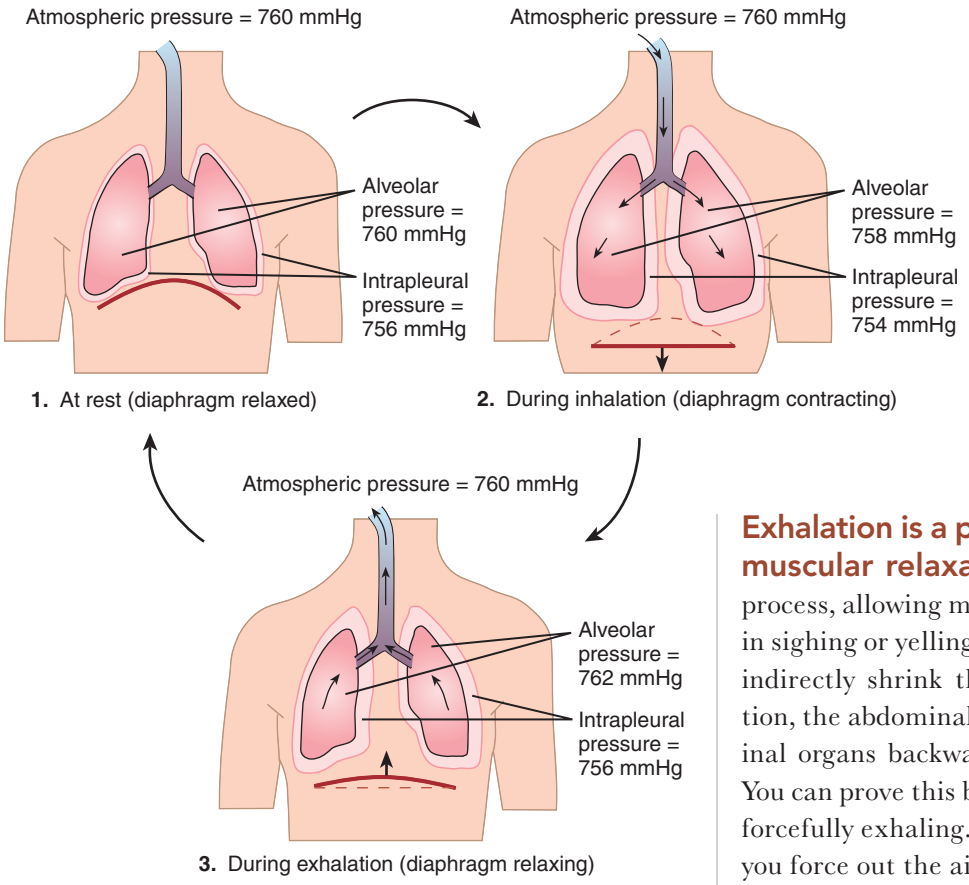
Muscles of inhalation and their actions (left); muscles of exhalation and their actions (right)

WILEY PLUS Interactivity

1. The diaphragm performs 75% of the work in normal respiration, with help from the intercostal, sternocleidomastoid, serratus anterior, pectoralis minor, and scalene muscles. You can identify these other muscles by watching in a mirror while inhaling deeply. Your neck and shoulder muscles will become more visible as they contract.
2. The lungs increase in volume as they follow the walls of the thoracic cavity, decreasing the pressure within them.
3. This pressure decrease sets up a pressure gradient, with the atmosphere outside the nose at higher pressure than the atmosphere deep within the lungs. Air moves into the lungs to equalize the pressure.
4. The diaphragm relaxes, the intercostals relax, and the thoracic cavity returns to its former size. The volume of the cavity decreases, increasing the pressure on the gases within the cavity. Contraction of the rectus abdominus and external oblique muscles will further decrease the thoracic cavity by pushing the digestive organs up against the diaphragm.
5. The gases within the cavity rush outward through the nostrils to again equalize pressure between the lungs and the environment. One complete cycle of pulmonary ventilation includes an inhalation and an exhalation.



Pressure changes in pulmonary ventilation • Figure 13.13



Pressure changes within the thoracic cavity occur as the volume of the cavity increases and decreases. During inhalation, the diaphragm contracts, the chest expands, and the lungs are pulled outward. All of these decrease pressure within the lungs, allowing air to rush in. Relaxing the diaphragm and the intercostals drops the volume of the lungs, increasing their pressure and forcing the air back out.

the thoracic cavity. The increasing volume of the lungs during inhalation causes the pressure to drop, in turn causing gas molecules to rush in from the environment outside your nostrils. Because air moves from high-pressure zones to low-pressure zones, air moves into your lungs to equilibrate this pressure gradient. This is how inhalation occurs.

When the muscles that expanded the thoracic cavity relax, the thoracic cavity returns to its original size, which raises pressure in the thoracic cavity above that outside the nostrils. See **Figure 13.13**. Again, because air moves toward areas of low pressure, the respired air exits the respiratory tract. During exhalation, the lungs act like a bicycle pump: The container holding the air shrinks, gas pressure rises and exceeds pressure outside the pump, so air must leave the container.

Drowning occurs when water, which is too heavy to be removed from the lungs, is pulled into them. Our respiratory muscles cannot expel the water, and water carries too little oxygen to diffuse into our blood. In fact, oxygen will diffuse in the opposite direction, from blood to the water!

Exhalation is a passive process, mainly involving muscular relaxation. Exhalation is usually a passive process, allowing muscles to relax. If we forcibly exhale, as in sighing or yelling, we contract muscles that directly and indirectly shrink the thoracic cavity. In forcible exhalation, the abdominal muscles contract, pushing the abdominal organs backward, upward, and into the diaphragm. You can prove this by placing a hand on your abdomen and forcefully exhaling. You will feel these muscles contract as you force out the air.

Recall that the alveoli are thin and moist. Surfactant helps prevent these membranes from gumming up and sticking together during exhalation. Another factor in the breathing process is the vacuum between the two layers of pleura. This vacuum forms during fetal development, when the walls of the thoracic cavity enlarge faster than the lungs. The parietal pleura is pulled outward with the expanding walls, while the visceral pleura remains attached to the lungs. The resulting vacuum is essential to respiration because it prevents collapse of the thin alveoli during exhalation. The walls of the alveoli spring inward as the air leaves the respiratory tract, but the alveolar walls do not collapse and stick together, partly because of the outward pull of the vacuum between the pleura. In addition, the slight vacuum helps the lungs enlarge and fill with air on the next inhalation.

Your Brain Stem Sets Your Respiratory Rate

As you read this text, you are breathing at a steady rate. These constant, day-in, day-out breaths are called your **resting rate**. Respiratory rate is governed by the medulla oblongata and the pons in the brain stem. The respiratory

center in the medulla oblongata causes rhythmic contractions of the diaphragm, stimulating contraction for two seconds and allowing three seconds of rest. This cycle repeats continuously unless overridden by higher brain function. You can override the medullary signal by holding your breath or by forcibly exhaling, but you cannot hold your breath until you die. Many small children use this threat to blackmail adults, but let them try! The pons will not let anybody "forget" to breathe.

The body can sense the levels of carbon dioxide and oxygen in the blood through **chemoreceptors** in the carotid artery and aorta. High carbon dioxide levels immediately trigger an increase in the depth and rate of respiration. These chemoreceptors respond to a 10% increase in carbon dioxide levels by doubling the respiratory rate. In contrast, a much larger decrease in oxygen level is needed before these receptors will cause the respiratory rate to rise.

chemoreceptors
Sensory receptors that detect small changes in levels of specific chemicals, such as carbon dioxide.

Different Respiratory Volumes Describe Different Types of Breath

During normal breathing, the volume of air inhaled per minute reflects the respiratory rate and the volume of each normal breath, called the **tidal volume (TV)**. Tidal volume, approximately 500 ml, is somewhat more than the amount of air that is actually exchanged, because the trachea, larynx, bronchi, and bronchioles are "anatomic dead spaces" that do not participate in gas exchange. These dead spaces have a volume of about 150 ml. Thus, each tidal breath delivers about 350 net ml of air to the respiratory membranes.

Just as you can consciously control your breathing rate, you can increase the volume of breath by contracting more muscles during inhalation. During a "forced inhalation," the average adult can inhale approximately 1,900 to 3,300 ml of additional air. This volume is called the **inspiratory reserve volume (IRV)**.

Similarly, we can exhale much more than the 500-ml tidal volume: up to 700 to 1,000 ml, in the **expiratory reserve volume (ERV)**. This volume is lower than the IRV because exhalation is largely passive; we have no muscles that directly compress the thoracic cavity beyond those used in a tidal breath. The best we can do is indirectly pressurize the thoracic cavity by contracting the abdominal muscles, forcing the contents of the abdominal cavity up against the diaphragm. We do this fairly often, as explained in *What a Scientist Sees: Using the Expiratory Reserve Volume.*

Vital capacity (VC) measures the total volume of air your lungs can inhale and exhale in one huge breath, which is essentially the maximum amount of air your lungs can

NATIONAL GEOGRAPHIC

WHAT A SCIENTIST SEES

Using the Expiratory Reserve Volume

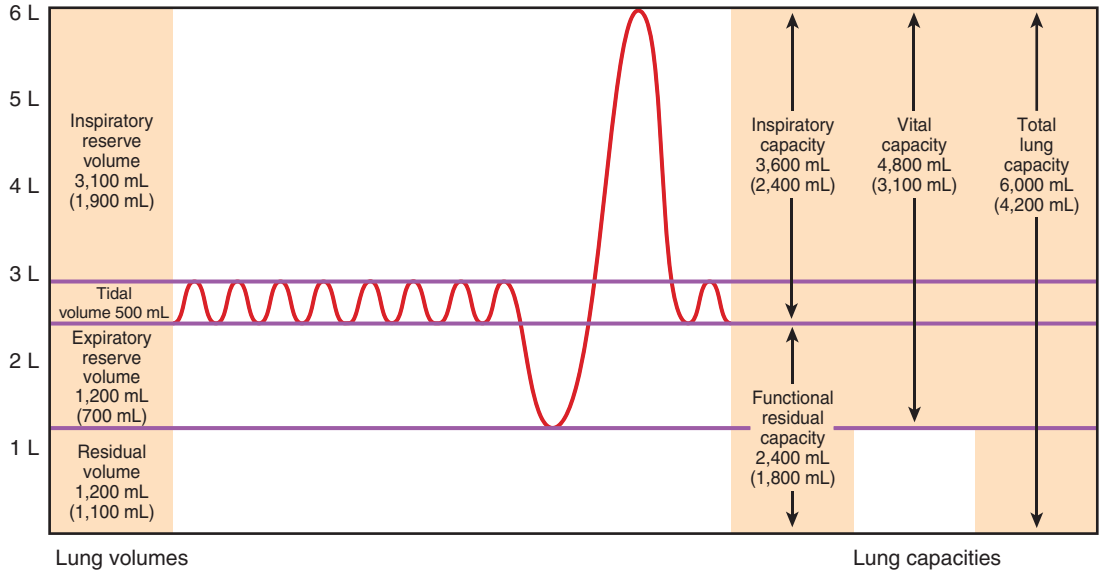
Normal tidal volume moves air in and out of the lungs without taxing the respiratory muscles. When a larger volume of air must be exchanged, the intercostals, the scalenes, and the abdominal muscles are used as well. In adults, the volume of air exhaled can increase from approximately 500 ml to over 3,000 ml. Even children have plenty of air for birthday rituals!

Think Critically

1. What muscles are being used by this 5-year-old boy as he prepares to blow out his candles?
2. How does the contraction of the rectus abdominus and intercostal muscles affect the volume of the thoracic cavity?
3. What respiratory volume is being used in this common birthday activity?

Respiratory volumes • Figure 13.14

Average respiratory volumes for both males and females. Female volumes are slightly smaller and are given in parentheses.



move in one respiratory cycle. See Figure 13.14. VC is the sum of inspiratory reserve volume, tidal volume, and expiratory reserve volume. For most people, the VC is between 3,100 and 4,800 ml; men generally have a larger volume than women, due to their larger size on average.

The amount of air that remains in the lungs after forced expiration is called the **residual volume (RV)**. The residual volume holds the alveoli open and fills the "anatomical dead spaces." The RV is usually between 1,100 and 1,200 ml. You can add your RV to your VC to find your total lung capacity.

Have you ever fallen from a tree or a swing and landed on your back? Perhaps you could not breathe for a minute because you had "gotten the wind knocked out of you." In our terms, your problem was a loss of residual volume. The force of impact momentarily shrank the thoracic cavity beyond the amount that muscular contractions could achieve and forced out some of the residual volume. Your first breath was painful and may even have produced awkward noises as you reinflated the empty alveoli to refill your RV. This is just what infants do with their first few gasps after birth (which are commonly mistaken for crying).

CONCEPT CHECK STOP

1. **How** does muscle activity promote inhalation and exhalation?
2. **What** triggers are used by the body to set breathing rate?
3. **What** is the relationship between ERV, IRV, and VC (vital capacity)?

13.3 External Respiration Brings Supplies for Internal Respiration

LEARNING OBJECTIVES

1. **Define** internal and external respiration.
2. **Discuss** the movement of gas from air to blood and from blood to tissues.

Thus far we have discussed only pulmonary ventilation—the moving of air into the respiratory system. Once gases are in the alveoli, **external respiration** occurs. **External respiration** is the exchange of gases between the air in the alveoli and the blood in the respiratory capillaries. A second respiratory process—**internal respiration**—is the exchange of gases between body cells and blood in the systemic capillaries.

External Respiration Secures Oxygen and Disposes of Carbon Dioxide

The exchanges during external and internal respiration are driven by the **partial pressures** of oxygen and carbon dioxide. In external respiration, the driving force is the difference in the partial pressures in the alveolar air and the capillary blood. In internal respiration, the driving force is the partial pressure difference in the capillary blood and the tissue fluid.

partial pressure
The percentage of total gas pressure exerted by a single gas in the mixture.

The air we breathe is composed of many gases. Nitrogen is the most common, making up 78.6% of the atmosphere by volume. Oxygen is the second most common gas, occupying 20.9% of total volume. Water vapor varies by location and weather, ranging from 0 to 4% of volume. Finally, carbon dioxide makes up a measly 0.04% of air by volume. The air pressure in any mass of air is a sum of the partial pressures of each constituent gas, so the pressure exerted by each gas is directly related to its proportion in the atmosphere. Thus, in air, 78.6% of the pressure is generated by nitrogen molecules, 20.9% by oxygen, and 0.04% by carbon dioxide. Knowing that atmospheric pressure is usually close to 760 mmHg, we can calculate the partial pressures of each gas.

Why discuss partial pressure? We discuss it because it explains the movement of oxygen and carbon dioxide in respiration. **Dalton's law** states that gases move independently down their pressure gradients, from higher to lower pressure. See **Figure 13.15**. As a result, oxygen will diffuse from the air in the alveoli into the blood, whereas carbon dioxide will diffuse from blood to the alveoli. Each gas independently moves toward an area of lower pressure without affecting any other gas.

The partial pressure of oxygen in the air of the alveoli is approximately 100 mmHg, whereas the partial pressure of oxygen in the tissues hovers near 40 mmHg. Through simple diffusion, oxygen moves from the air in the alveoli through the thin respiratory membrane and into the blood. By the time blood in the respiratory capillaries completes its journey through the lungs, the partial pressure of oxygen in the blood has equilibrated with the partial pressure of the oxygen in the air in the alveoli. Blood returning to the heart's left atrium carries oxygen with a partial pressure of 100 mmHg, ready to be pumped to the tissues.

While oxygen is diffusing into the blood, carbon dioxide is leaving it. The partial pressure of carbon dioxide in the blood returning to the left side of the heart is about 40 mmHg. Blood picks up carbon dioxide as it courses through the tissues, and by the time it reaches the alveoli, the partial pressure of carbon dioxide is 45 mmHg, higher than the CO_2 pressure of 40 mmHg in the alveolar air. This CO_2 pressure gradient causes carbon dioxide to diffuse from the blood to the alveolar air. When the blood leaves the lungs and enters the left atrium, its carbon dioxide partial pressure has dropped to 40 mmHg. The difference between 40 and 45 mmHg tells us how much of this waste gas was removed from the body.

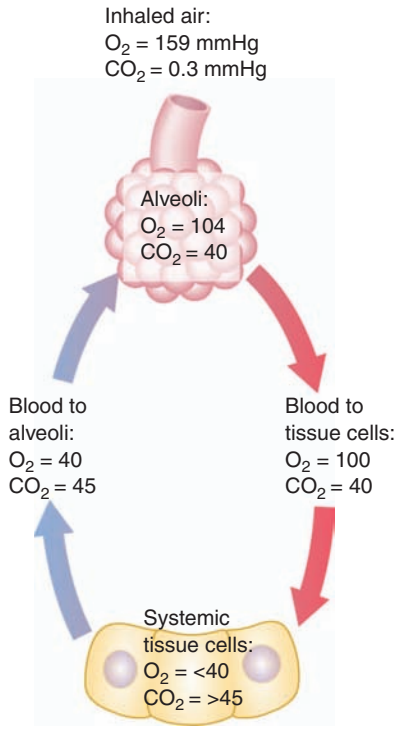
Internal Respiration Supplies Oxygen to the Cells and Removes Their Gaseous Waste

Internal respiration is the exchange of gases between the blood and the cells, as shown in Figure 13.15. For survival,

Dalton's law • Figure 13.15

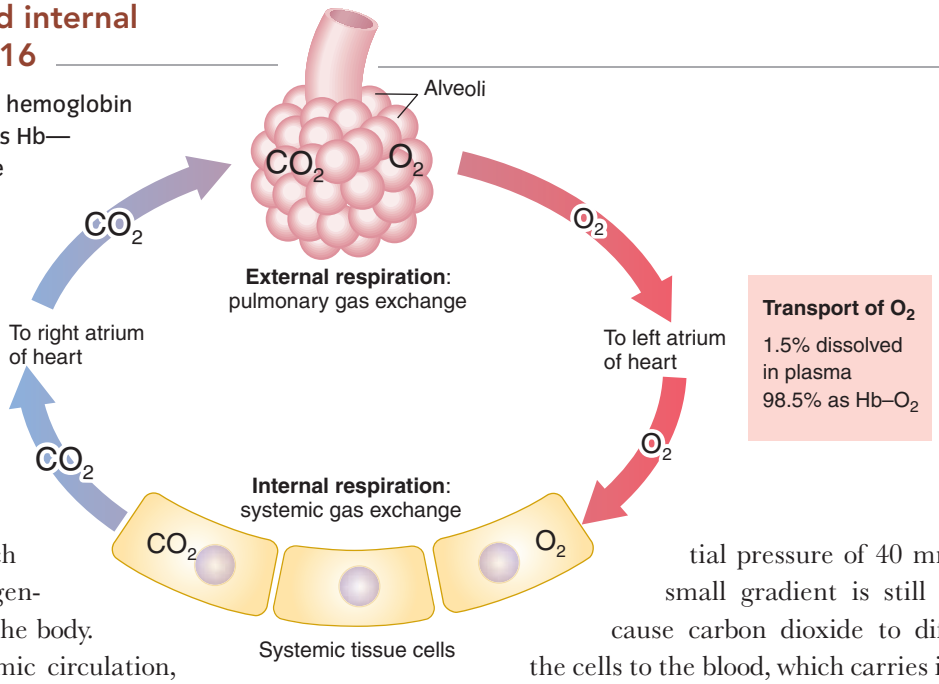
Each gas in the atmosphere exerts its own partial pressure, which all add up to total atmospheric pressure. Each gas can independently diffuse from areas of high concentration to areas of low concentration.

Partial pressures in atmosphere:	
Nitrogen (P_{N_2})	597.4 mmHg (78.6%)
Oxygen (P_{O_2})	158.8 mmHg (20.9%)
Carbon dioxide (P_{CO_2})	0.3 mmHg (0.04%)
Other gases ($P_{other\ gases}$)	3.5 mmHg (0.46%)
Total:	760.0 mmHg (100%)



Summary of external and internal respiration • Figure 13.16

Most oxygen is transported by the hemoglobin (Hb) of the red blood cells (RBCs) as Hb—O_2. Carbon dioxide is carried in the blood plasma as bicarbonate ions (HCO_3^-) and by the hemoglobin of RBCs as Hb—CO_2.



oxygen in the arteries must reach the tissues, and carbon dioxide generated in the cells must leave the body. In the capillaries of the systemic circulation, the two gases again diffuse in opposite directions. Oxygen enters the tissues, and carbon dioxide diffuses out of the tissues, again based on partial pressure. The partial pressure of oxygen in the capillary beds of the systemic circuit is approximately 95 mmHg, whereas the partial pressure of oxygen in most tissues is about 40 mmHg. This gradient allows oxygen to leave the blood and enter the respiring cells without requiring energy from the body.

Cellular respiration produces carbon dioxide, and the partial pressure of carbon dioxide in the tissues is about 45 mmHg. Blood in the capillary beds has a carbon dioxide partial pressure of 40 mmHg. This small gradient is still enough to cause carbon dioxide to diffuse from the cells to the blood, which carries it off to the lungs for release into the alveolar air. This process is illustrated in **Figure 13.16**.

CONCEPT CHECK

STOP

1. **Which** type of respiration is responsible for delivering oxygen to the tissues of the body: external or internal respiration? **Which** is responsible for obtaining oxygen from the air?
2. **How** does oxygen move from air to blood and from blood to tissues?

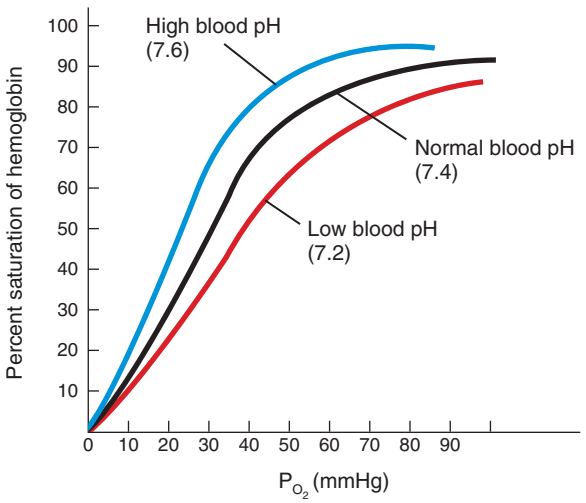
13.4 Transport of Oxygen and Carbon Dioxide Requires Hemoglobin and Plasma

LEARNING OBJECTIVES

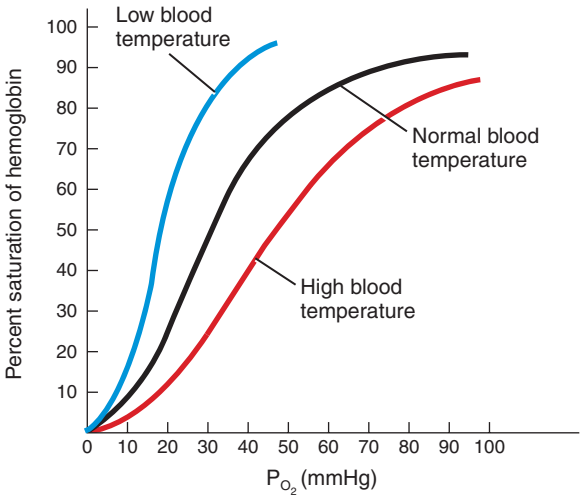
1. **Understand** the role of hemoglobin in respiration.
2. **Recognize** the role of carbon dioxide in maintaining blood pH.

Respiration involves not only the structures of the respiratory system but also the functioning of the cardiovascular system. As we have seen, the respiratory system moves the gases in and out of the body, while the cardiovascular system transports them within the body. Oxygen moves from the air to the lungs, where it diffuses into the capillaries of the lungs, while carbon dioxide follows an opposite path, moving from the tissues to the blood and out via the lungs. The pulmonary capillaries exchange gases in

Effects of pH and temperature on hemoglobin binding • Figure 13.17



a. Effect of pH on hemoglobin's affinity for oxygen



b. Effect of temperature on hemoglobin's affinity for oxygen

the lungs, while the systemic capillaries exchange gases in the body. The final piece to this puzzle is to determine how these gases are carried through the cardiovascular system between the two capillary beds.

Hemoglobin Transports Oxygen

As we know, the **hemoglobin** molecule carries oxygen in the blood. Hemoglobin picks up oxygen through a bond between the oxygen molecule and the iron atom of the heme molecule. Hemoglobin has a high **affinity** for oxygen under some conditions but will release it under other conditions. The oxygen–hemoglobin dissociation curves discussed in Chapter 12 and reviewed below show hemoglobin's unique characteristics.

affinity An attraction between particles that increases chances of their combining.

The bond between oxygen and hemoglobin is reversible. Oxygen binds to the iron atom in the hemoglobin molecule when the partial pressure of oxygen is high, the pH is high, and the temperature is low. In areas where these conditions do not exist, hemoglobin releases oxygen. Even minute changes in temperature or pH will cause oxygen release, as seen in Figure 13.17. Such differences exist in active tissue—muscles generate heat while contracting, which warms the muscle. Contraction requires oxygen to fuel ATP production, which produces lactic acid, which lowers the pH. Both of these factors increase oxygen delivery to the muscle cells.

Several Mechanisms Transport Carbon Dioxide

Hemoglobin is best known for carrying oxygen, but it also conveys about 23% of total carbon dioxide through the bloodstream. This carbon dioxide binds to the protein portion of hemoglobin, forming **carbaminohemoglobin ($Hb—CO_2$)**.

Another 7% of the blood-borne carbon dioxide is carried as dissolved CO_2 gas. The major share of blood-borne carbon dioxide (about 70% of total carbon dioxide) moves as **bicarbonate ions** in plasma. A bicarbonate ion is produced in steps. First, carbon dioxide and water combine to form carbonic acid inside red blood cells. The enzyme **carbonic anhydrase** speeds this reaction, allowing red blood cells to remove most of the carbon dioxide from the blood. This carbonic acid then dissociates into a hydrogen ion and a bicarbonate ion. The hydrogen ion is picked up by hemoglobin, forming **reduced hemoglobin**. The bicarbonate ion is transferred out of the RBC in exchange for a chloride ion entering the RBC. The large transport of chloride ions into the RBCs, called the **chloride shift**, is an exchange reaction that requires no ATP, because it merely switches the positions of the anions. The bicarbonate ion in the plasma then serves as a **buffer**, helping

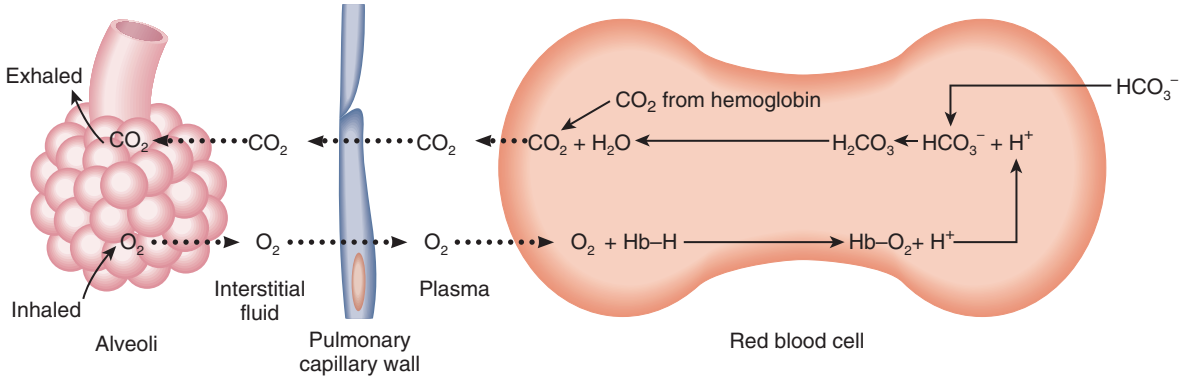
bicarbonate ion HCO_3^-, a buffering ion.

buffer A compound that absorbs hydrogen ions or hydroxide ions, stabilizing pH.

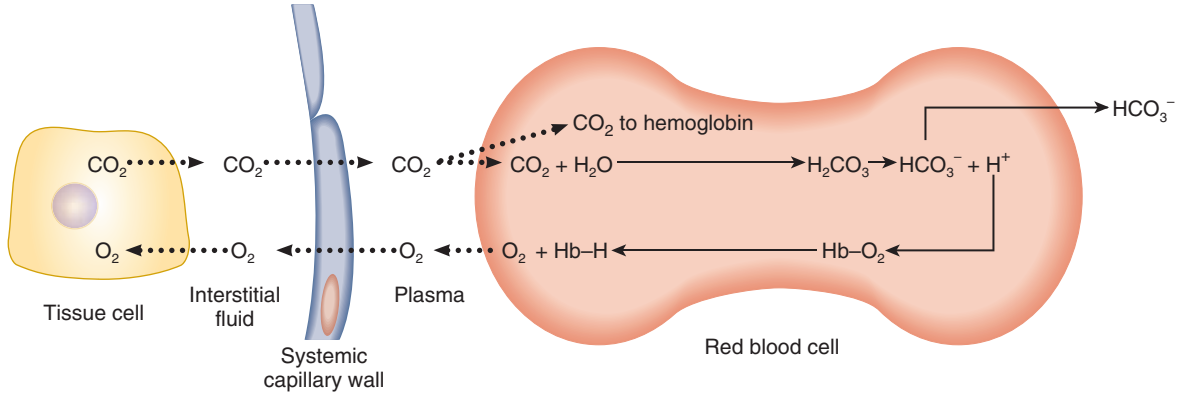
PROCESS DIAGRAM

THE PLANNER

Carbon dioxide transport in blood • Figure 13.18



a. Exchange of O_2 and CO_2 in pulmonary capillaries (external respiration)
The bicarbonate ion is absorbed from the blood into the RBC, where it is converted to carbon dioxide and passed out to the alveolus. Oxygen is also entering the RBC at the alveolus.



b. Exchange of O_2 and CO_2 in systemic capillaries (internal respiration)
Carbon dioxide is passing from the tissues to the capillaries, where it is picked up by the RBC. Inside the RBC, the carbon dioxide is converted to bicarbonate ions that are then pumped back out to the blood, where they serve as a buffer. Oxygen is seen leaving the RBC and diffusing into the tissues, where it is used to drive cellular activities.

to maintain blood pH—see **Figure 13.18**. Without this buffering, we could not control our internal pH, and we would perish.

Reduced hemoglobin is a deep crimson, almost purple color, which is partially why venous blood looks so blue when viewed through our skin. The red color of arterial blood is due to a high concentration of **oxyhemoglobin** ($Hb—O_2$). However, blood inside your body is never as crimson as the blood that is spilled when you cut yourself. The partial pressure of oxygen in the atmosphere is far higher than anywhere in your body, so hemoglobin quickly picks up more oxygen when you bleed.

oxyhemoglobin
Hemoglobin molecule with at least one oxygen molecule bound to the iron center.

CONCEPT CHECK

STOP

1. **What** characteristics of hemoglobin make it ideal for oxygen transport? In other words, **when** does hemoglobin pick up oxygen, and under **what** conditions does it release it?
2. **What** is one positive role of carbon dioxide in the blood?

13.5 Respiratory Health Is Critical to Survival

LEARNING OBJECTIVES

1. **Discuss** two common disorders of the upper respiratory tract.
2. **Identify** the symptoms of obstructive respiratory disorders.
3. **Describe** the main disorders of the lower respiratory tract.

The previous chapter introduced cardiovascular disorders and outlined their obvious impact on respiration. If the blood does not circulate properly, or if it does not carry enough oxygen, external and internal respiration are impaired.

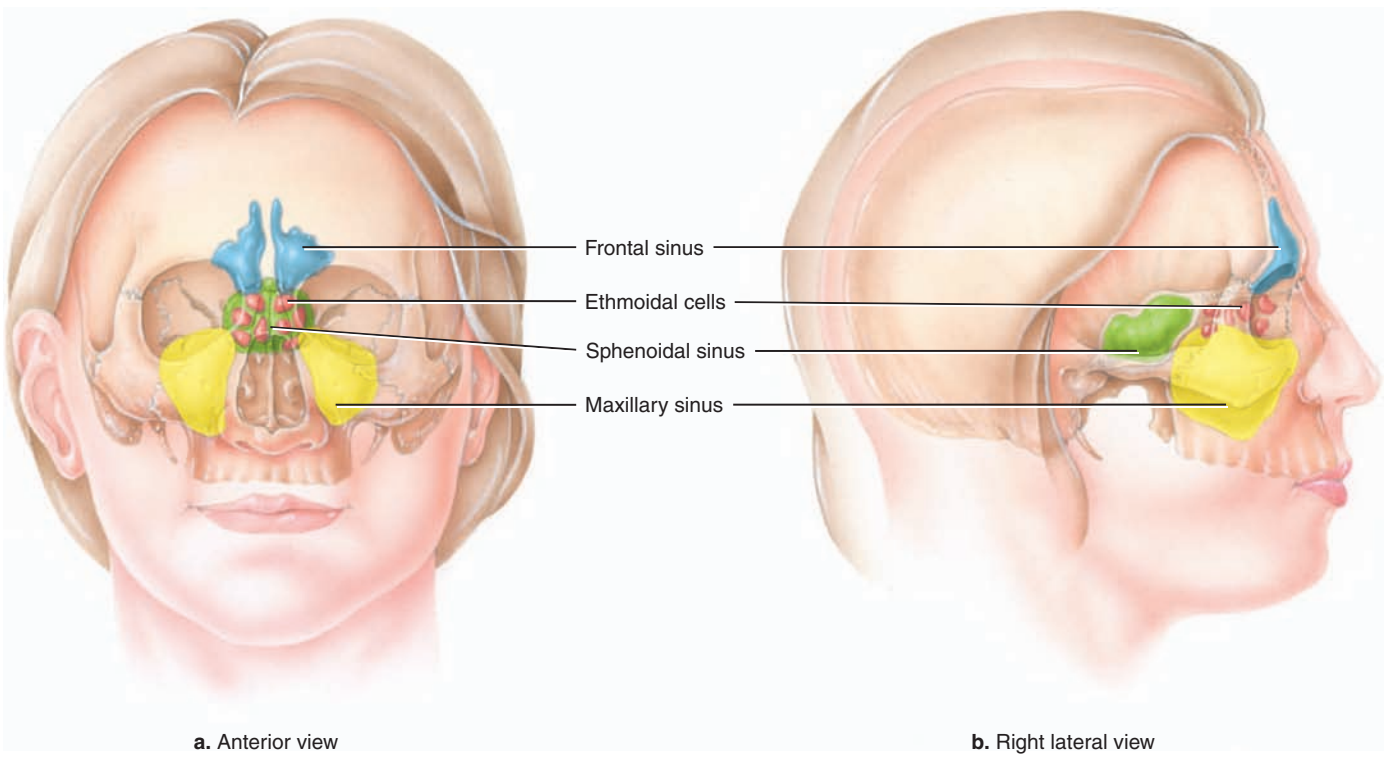
The upper respiratory tract is susceptible to infection and inflammation of the nasal passages, sinuses, and larynx. One of the most common upper respiratory diseases is **sinusitis**, an inflammation or swelling of the sinuses (*-itis* means inflammation). **Sinuses** are cavities in the skull, lined with the same type of mucous membrane as the nasal passages. See Figure 13.19. Sinuses exist in the frontal, ethmoid, sphenoid, and maxillary bones, but the largest are in the frontal bone. When you succumb to the common cold or flu, viruses swell the nasal membranes. **Histamines** are released, and mucus production increases as the membranes try to rid the body of the virus. If the membrane lining a sinus swells, the opening can shut, preventing mucus produced in the sinus from draining and causing it to build up pressure in the closed sinus. Resident populations of streptococcus or staphylococcus bacteria can also grow unchecked in the closed sinus. **Acute sinusitis** is usually caused by a common cold and goes away on its own within two to three weeks. **Chronic sinusitis**, in contrast, is more severe and its causes are less clear. Most people who suffer from chronic sinusitis also have allergies, asthma, or a compromised immune system

histamine A compound involved in allergic reactions that causes capillary leakage and increased fluid movement to affected tissues.

acute sinusitis Inflammation of the sinuses with sudden onset and usually of short duration.

chronic sinusitis Inflammation of the sinuses that persists for long periods of time.

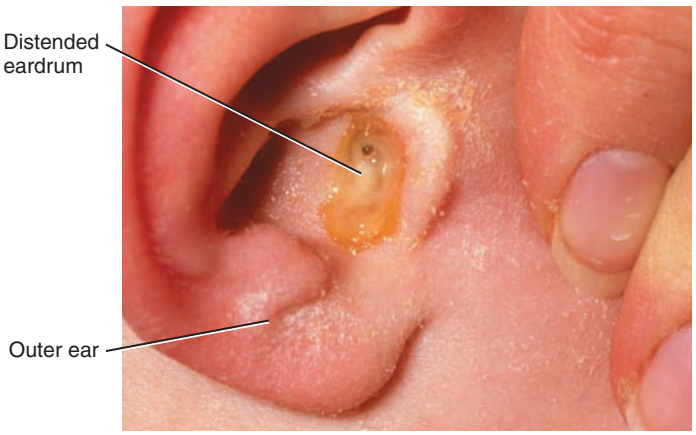
Sinuses • Figure 13.19



a. Anterior view

b. Right lateral view

Distended eardrum caused by otitis media • Figure 13.20



due to a disease like AIDS. Treating this type of sinusitis is also more difficult; antibiotics, inhalant steroids, or even oral steroids may be used, depending on the case.

If you have a young child, you probably know about **otitis media**, shown in Figure 13.20. This inflammation of the middle ear fills the middle ear with fluid, distending the eardrum. A stretched eardrum can cause severe pain, and the eardrum can rupture as bacteria within the trapped fluid multiply. Otitis media is usually caused by a bacterial infection that can be treated with antibiotics. The pathogens most often arrive through the eustachian tube, with its open connection between the middle ear and the nasopharynx. In small children, the tube is almost horizontal, so fluids in the mouth can easily travel to the middle ear, especially since the bottom of the tube opens with each swallow. As we age, our facial bones expand, tilting the eustachian tubes toward the vertical, so fluids do not flow so readily to the middle ear. For this reason, ear infection rates drop with age.

Diseases of the lower respiratory tract are usually either **obstructive**, meaning that something is obstructing the normal flow of gases through the lungs, or **constrictive**, indicating that the airways have been narrowed in some way.

Constrictive Diseases Are Serious but Often Sporadic

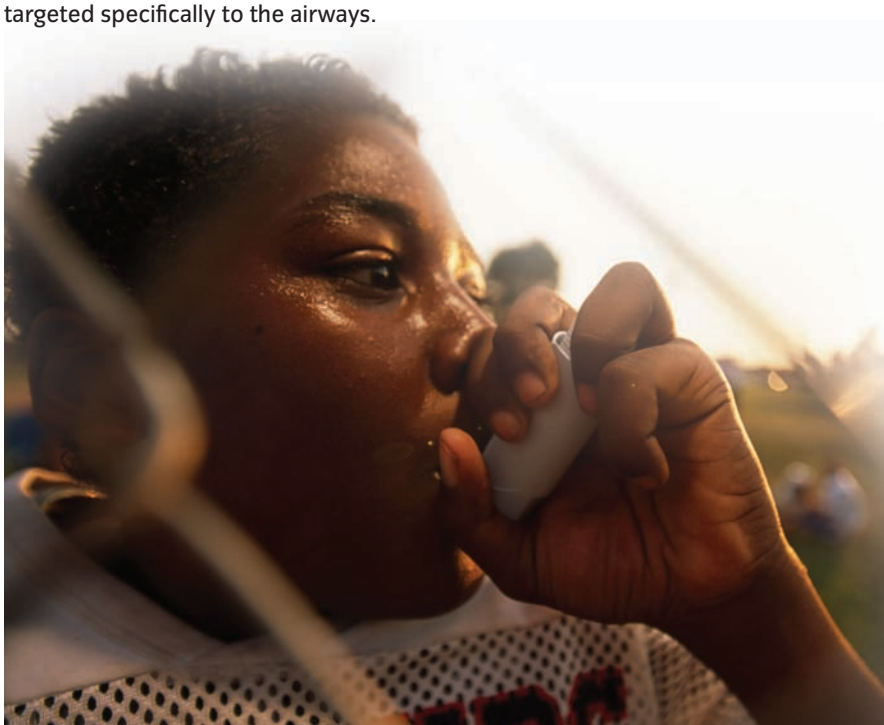
As the name implies, constrictive respiratory diseases constrict the airways. One common constrictive disease of the lower respiratory tract is **bronchitis**, an inflammation of the mucous membrane lining the bronchi. When this membrane swells, the lumen of the bronchiole constricts. Often these infected bronchioles also produce more mucus, which can block air passages. The most common symptom of bronchitis is a deep, often painful, cough. Acute bronchitis can be caused by viruses and occasionally bacteria. Chronic bronchitis is most often caused by smoking and can last from months to years, depending on the severity of the reaction to smoke and the duration of the smoking habit. The main symptom of acute and chronic bronchitis is a productive cough. In acute bronchitis, shortness of breath, tightness of the chest, and a general feeling of illness often accompany the cough. Treatment for bronchitis includes rest, plenty of fluids, and perhaps over-the-counter cough medicine. If the cough persists, an inhalant **bronchodilator**, shown in Figure 13.21, may be prescribed to relax the smooth muscle of the bronchi, open the constricted tubes, and help clear the mucus.

Asthma is a constrictive pulmonary disease that can be life-threatening. During an asthma attack, the smooth muscle of the bronchi contracts, mucus production increases in these tubes, and the bronchi swell, interfering with the passage of air. Breathing grows laborious, and wheezing is common during exhalation. Asthma attacks are usually triggered by an external source, such as exercise, viral infection, or inhalation of cold air or an allergen, or by high levels of ozone in the air.

Asthma may result from an overactive immune system, and, for many people, inhaling an allergen can cause an immediate, dangerous airway constriction. Many asthma patients carry inhalers containing bronchodilator drugs to

Asthmatic treatment for immediate respiratory relief • Figure 13.21

Inhalers contain bronchodilator drugs, such as albuterol. Albuterol is a derivative of epinephrine with fewer side effects, targeted specifically to the airways.



quickly open the airways during an attack. As a preventive measure between attacks, many chronic asthmatics inhale corticosteroids to reduce the number and severity of asthma attacks. Despite these medicines, however, asthma still kills up to 5,000 people every year in the United States.

Obstructive Diseases Cause Permanent Lung Damage

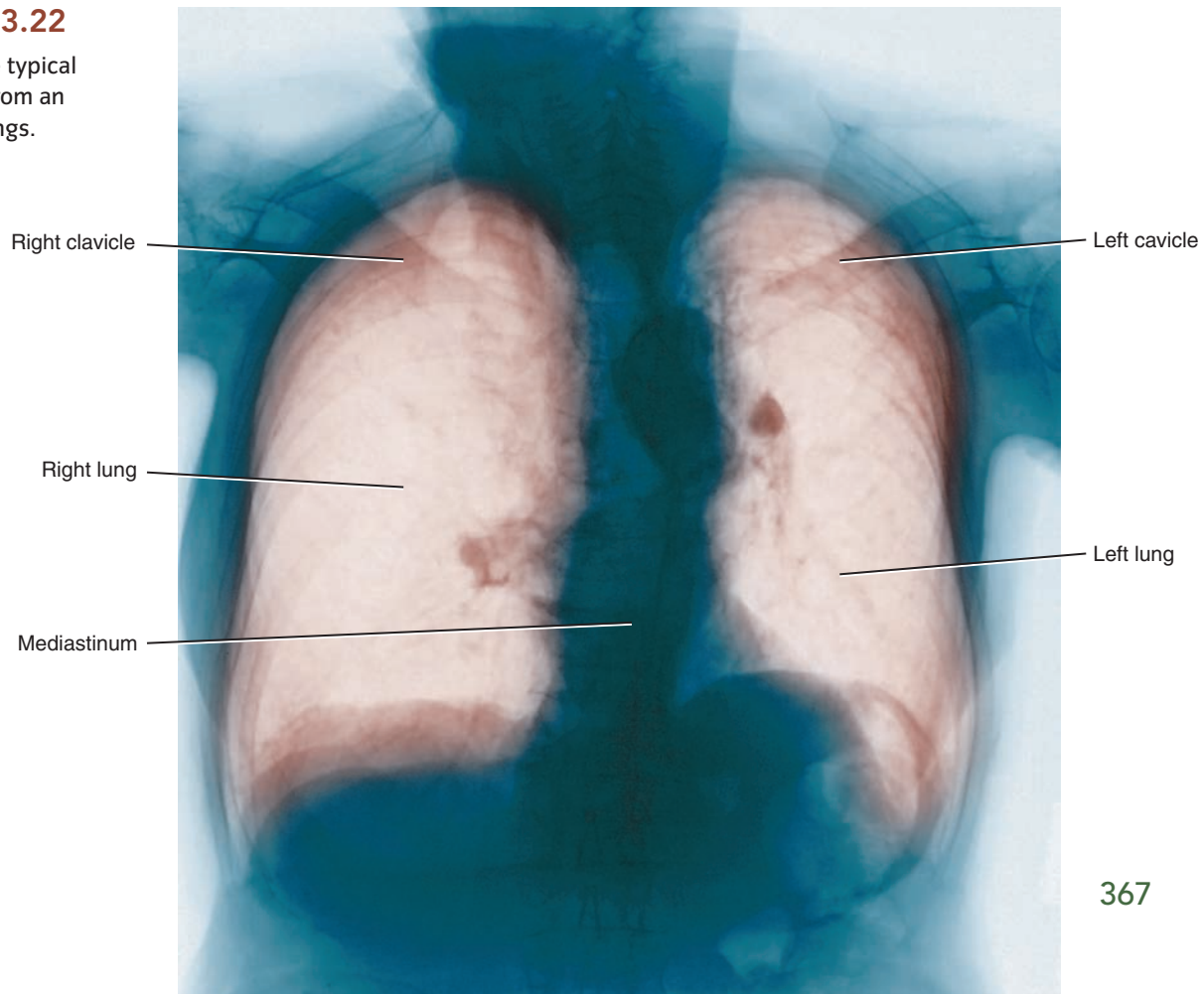
Although asthma is a serious disease, it does not permanently damage lung tissue. In contrast, the chronic obstructive pulmonary diseases, including **emphysema** and cystic fibrosis, do damage or destroy the terminal and respiratory bronchioles. The most common obstructive pulmonary diseases are **pneumonia**, **tuberculosis**, **emphysema**, and **lung cancer**. After exhalation in all of these diseases, the tubes of the airway do not spring back open, because the elastic tissue is destroyed. Pressure builds in the lungs as the patient tries to force air through the collapsed tubes, damaging the delicate alveoli and reducing the respiratory surface area. This results in the typical "barrel chest" appearance of COPD sufferers, as shown in Figure 13.22. The most common cause of emphysema is smoking, but environmental pollutants and even genetic factors can also be to blame. Pulmonary fibrosis, a destructive increase in collagen that also makes the lungs less elastic, often results from occupational exposure to silicon or other irritants.

Why is chronic obstructive pulmonary disease so deadly? Chronic obstructive pulmonary disease (COPD) is actually two diseases—emphysema and chronic bronchitis—that both diminish and obstruct airflow. (Doctors use *COPD* to describe this combination because individual patients often have both diseases.) In the United States, the death rate from COPD has doubled in the past 30 years, to an estimated 120,000 annually. Globally, scientists predict that COPD will be the third-largest cause of death by 2020. The major cause is cigarette smoking, but other airborne toxins and pollutants are also to blame.

Emphysema begins when a pollutant or cigarette smoke damages the alveoli, forming holes that cannot be repaired. Delicate lung structures become fibrotic (filled with fibers) and stiff, reducing their elasticity and making exhaling difficult. The disease starts gradually, with a shortness of breath, and gets worse with age. Smoking causes more than 80% of such cases. About 5% of Americans suffer from genetic emphysema caused by the lack of a protein necessary for lung function.

COPD • Figure 13.22

COPD victim showing the typical barrel chest that arises from an inability to deflate the lungs.



Both types of COPD reduce gas transfer in the lungs, causing shortness of breath. Exercise, and even daily activity, become difficult or impossible. COPD may be treated with antibiotics to kill the bacteria in the alveoli, and anti-inflammatories and bronchodilators, which open the airways to ease breathing. Advanced emphysema patients need supplemental oxygen. An increasing number of COPD patients are receiving lung transplants. Although transplants can prolong survival, lungs have a shorter survival expectancy and often fail much sooner than other transplanted organs.

Given the increasing death rate and the fact that emphysema is invariably fatal, new perspectives are

NATIONAL GEOGRAPHIC

ETHICS AND ISSUES

When Does Particulate Air Pollution Become a Serious Public Health Hazard?

In the course of our lives, our respiratory systems cycle an enormous volume of air, including pollutants contained in that air. There are several forms of air pollution, but one of the most insidious is particulate matter (PM), a mixture of solids and liquid droplets. The smaller the particles, the greater the chance that coughing and sneezing won't remove them from our lungs and thus from our bodies. Particles less than 2.5 micrometers in diameter (less than 1/3 of the diameter of a human hair) carry the greatest risks to respiratory health because they get deeper into the lungs, and hundreds of studies have demonstrated a link between PM pollution and decreased lung function. If the lungs are not working properly, external respiration is compromised. Blood oxygen levels are lower, and internal respiration is also compromised. Tissues are not able to obtain the oxygen they require, leading to tissue damage and possibly organ failure.

There are many sources of PM, but two of the most common are vehicle exhaust and emissions from coal-fired power plants. The toxicity of PM depends on several factors: the particles' solubility and surface area, their concentration and chemical reactivity, and the duration of our exposure to them. Extreme particulate air pollution is undoubtedly very harmful to our respiratory (and cardiovascular) systems. A notorious recent example is the witch's brew of glass fibers, pulverized concrete, silicon, and various metals that circulated around and then downwind from the collapsed World Trade Center site during and after September 11, 2001.

PM pollution becomes controversial when scientists, industry groups, and policymakers try to agree on a common set of data that can serve as the basis for a standard of "acceptable" levels of PM pollution. Controlled studies of PM's effects on humans are few and far between. It is difficult to measure PM exposure and responses accurately, and we still don't understand the mechanisms by which PM pollution leads to specific diseases. Ironically, the prevalence of smoking makes it hard to interpret the results of some studies, because smoking is a variable whose effects on the lungs' response to PM need to be taken into consideration. Moreover, studies of PM pollution are attacked or defended using complicated statistical techniques, making the subject even harder for nonscientist policymakers to understand. It is even argued that exposure to PM pollution can be good for respiratory health, since it may strengthen the immune system.

Critical Reasoning Issues Several industry groups and political leaders argue that if stricter PM standards are established, many businesses will go under because of the costs of pollution abatement. Some tend to frame the issue as an all-or-nothing proposition.

Think Critically

1. Support or defend the idea that PM pollution should be thought of as similar to microbes that attack and therefore strengthen our immune systems.
2. Could the claim that businesses will fail if PM standards are stricter be a case of a false dichotomy—an either-or line of argument that ignores the complexity of the situation?
3. Given that all aspects of PM exposure and responses are not known definitively, would you recommend that policymakers take no further action to limit PM pollution?

needed on COPD. An intensified battle against smoking is an obvious first step that could bring many other benefits. Researchers have found other clues that could help explain and treat COPD. For example, a 20-year study found that asthmatics were 12 times as likely to develop emphysema as other people. Asthma and emphysema are considered separate diseases, but this evidence suggests that the emphysema epidemic may be related to the asthma epidemic. See *Ethics and Issues: When Does Particulate Air Pollution Become a Serious Public Health Hazard?*

Bacteria cause two more obstructive respiratory diseases. Lung tissue must remain warm and moist, because gases cannot diffuse across a dry membrane. Unfortunately, these same conditions are perfect for bacterial growth. Bacteria living in the warm, moist, lung tissue cause two of the more common obstructive respiratory diseases: **pneumonia** and **tuberculosis**.

Pneumonia is a general term for a buildup of fluid in the lung, often as a response to bacterial or viral infection. When the delicate membranes in the alveoli become inflamed, they secrete fluid in an attempt to eradicate the pathogen, but this fluid inhibits gas exchange across the membrane. Symptoms of pneumonia include a productive cough, lethargy, fever, chills, and shortness of breath. Treatment depends on the underlying cause of the fluid buildup. Although pneumonia usually can be treated, it can be fatal, especially in patients with weak immunity because of other serious illnesses.

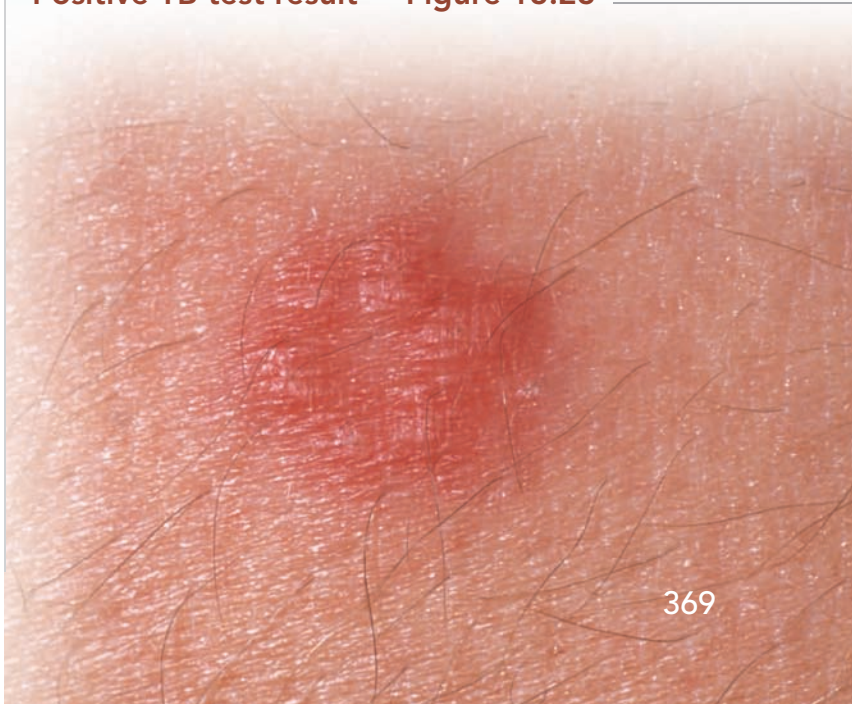
Tuberculosis (TB) is a disease caused by *Mycobacterium tuberculosis* infection. This tiny bacterium can pass from person to person in airborne droplets generated by a sneeze or cough. The inhaled bacteria multiply from one small region of the infected organ, called the "focus." Because it is airborne, the focus in humans is usually in the lung tissue. If the immune system can combat the disease, scar tissue may form at the focus. In those rare instances where the body does not eliminate the infection, the bacteria can enter the lymphatic system and infect just about any organ. The bacterium can also remain dormant for years and then reappear in the lungs without warning. Symptoms of TB resemble those of pneumonia, including a productive (and often bloody) cough, fever, chills, and shortness of breath. TB also causes weight loss and night sweats. TB is usually diagnosed if a focus appears on a chest X-ray. Previous exposure can be detected with a simple skin test, which is mandatory for children entering U.S. public schools. See Figure 13.23.

A century ago, TB was a major deadly health threat, but antibiotics have reduced the incidence in industrialized nations. Unfortunately, TB is on the rise again because antibiotic-resistant strains have now appeared, and many patients must take multiple antibiotics for many months to clear the infection. TB is one of several cases in which bacteria are starting to evade antibiotics that once controlled them. This shows how misuse of antibiotics, combined with their widespread use in animal agriculture, may help breed antibiotic-resistant strains of bacteria.

Lung cancer causes one-third of all cancer deaths. **Cancer** can attack just about any organ system, but lung cancer causes one-third of all cancer deaths in the United States. Lung cancer can affect the bronchi or the alveoli. In either case, the cells proliferate, obstruct airflow, and prevent gas exchange, as discussed in Chapter 11. Lung cancer is primarily due to tobacco smoking; nearly 90% of all lung cancer patients in the United States are current or former smokers. See *Health, Wellness, and Disease: Tobacco, the Universal Poison*. Lung cancer takes years to develop, and the risk increases with each year of smoking. The good news is that quitting smoking reduces the risk, even for long-term smokers. Unlike other cancers, lung cancer is relatively easy to prevent. Avoid smoking and exposure to environmental carcinogens, such as asbestos, silicon, coal dust, and radon gas.

Cystic fibrosis is a genetic disorder. **Cystic fibrosis** (CF) results from a defective gene that controls the consistency of mucus in the lungs. The CF version of this gene causes thick, sticky mucus to be produced, rather than thin, fluid mucus that is conducive to diffusion. The

Positive TB test result • Figure 13.23



HEALTH, WELLNESS, AND DISEASE

NATIONAL GEOGRAPHIC

Tobacco, the Universal Poison

In 1964, the U.S. Surgeon General issued an influential Report on Smoking and Health. The report looks tame today, given how much we now know about the toxicity of tobacco smoke, but it was an early acknowledgment that smoking causes lung cancer. Today, smoking-related lung cancer kills an estimated 174,000 people in the United States per year, and the number is rising.

Some of the approximately 4,000 compounds in tobacco smoke attack the delicate epithelial cells lining the respiratory tract and allow them to grow without control—the hallmark of cancer. Because early tumors are invisible, lung cancer is not usually detected until it has spread; therefore, the five-year survival rate is only 15%. Smoking and tobacco smoke also:

- Increase the risk of acute myeloid leukemia and cancer of the throat, mouth, bladder, kidney, stomach, cervix, and pancreas, according to the American Cancer Society.
- Impair several functions of the uterine tube, which conducts both gametes and the embryo, and alters female hormone effectiveness. Both effects could explain why smoking women have higher rates of reproductive problems, including undersized and/or premature infants.
- Kill nerve cells, interfering with smell and taste.
- Increase the risk of heart disease by a factor of 2 to 4.
- Raise the level of carbon monoxide and reduce the level of oxygen in the blood, which in turn reduce the ability to exercise or even move about comfortably.
- Destroy cilia in the airways, reducing the ability to expel mucus.

CF patient • Figure 13.24

The patient is receiving physical therapy, "clapping," to mobilize mucus in the lungs.

thick mucus traps bacteria and slows airflow through the bronchial tree, and it may also block the pancreas and bile duct. Treatment for the lung obstruction includes physical therapy to dislodge the mucus (see **Figure 13.24**) and new drugs that may make the mucus more fluid. Approximately 30,000 people in the United States are currently living with cystic fibrosis. Another 1,000 are diagnosed yearly, usually before age 3. One promising line of research would use gene therapy to correct the defect that causes CF.

CONCEPT CHECK

STOP

1. **What** are two common disorders of the upper respiratory tract?
2. **How** would you know if someone were suffering from pneumonia? **What** symptoms would they display?
3. **How** does asthma interfere with respiration?

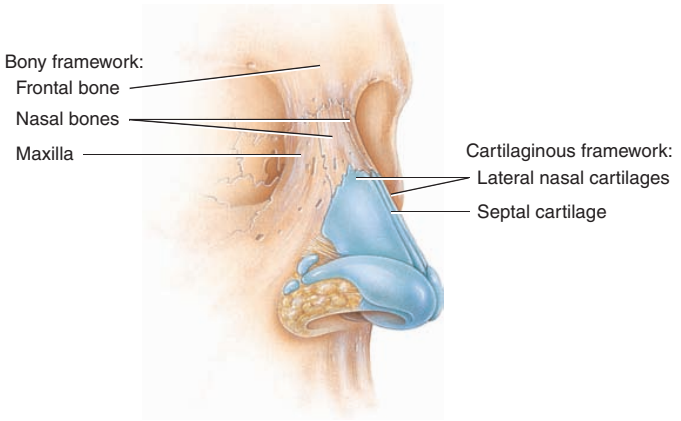
Summary

THE PLANNER

1 The Respiratory System Provides Us with Essential Gas Exchange 346

- The respiratory system delivers oxygen and removes carbon dioxide, helps balance blood pH, sustains fluid and thermal homeostasis, and produces speech in the larynx.
- The **upper respiratory tract** warms, moistens, and filters incoming air. The **lower respiratory tract** exchanges gas with the environment. The bronchial tree reaches into the lobes of the lungs. At the end of the respiratory bronchioles are the alveoli, the thin membranous sacs where gas exchange occurs.
- Septal cells produce surfactant to prevent the alveolar membranes from sticking together. Dust cells patrol the respiratory membrane to remove foreign particles.

Figure 13.2



a. Anterolateral view of external portion of nose

2 Air Must Be Moved in and out of the Respiratory System 356

- As shown here, pulmonary ventilation is the movement of air in and out of the lungs, based on Boyle's law of gases. Tidal volume is the amount of air you inspire during a normal, quiet inhalation.
- Your vital capacity, the total amount of air you can move in and out during one breath, is the sum of tidal volume, inspired respiratory volume, and expired respiratory volume. Residual volume is the volume of air that you cannot remove from the lungs.

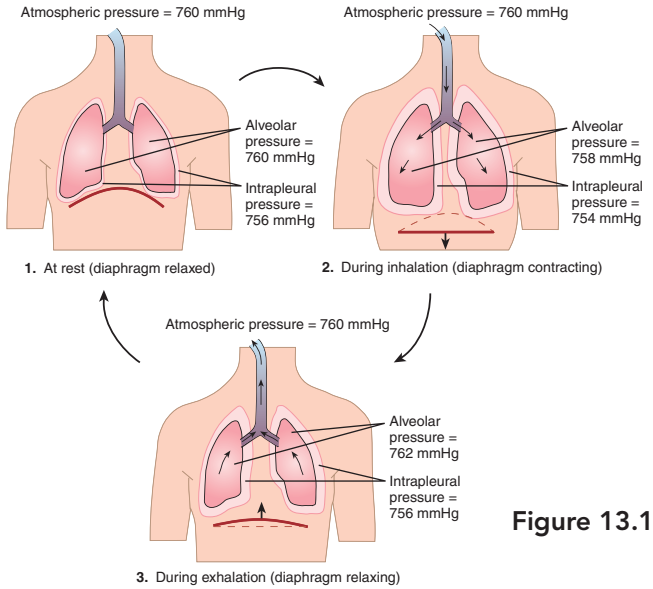
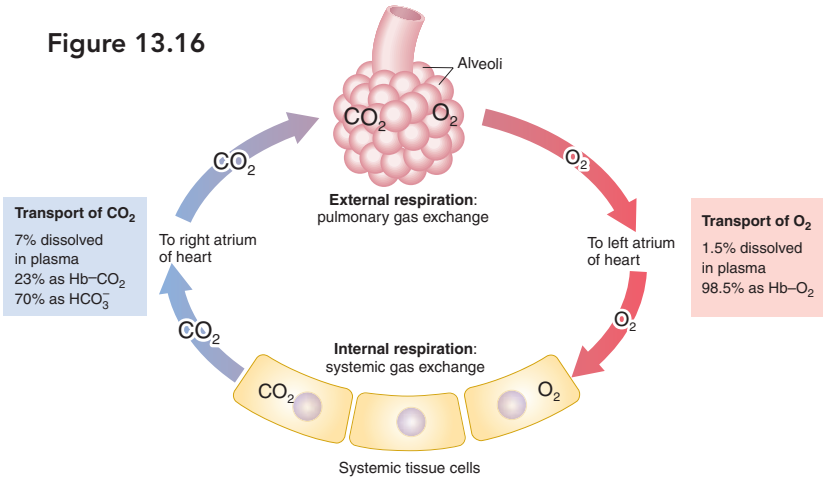


Figure 13.13

3 External Respiration Brings Supplies for Internal Respiration 360

- External respiration is the exchange of gases between air in the alveoli and blood in the pulmonary capillaries. Oxygen enters the red blood cells, while carbon dioxide exits. Internal respiration is the transfer of gases between systemic capillaries and body cells. A summary of external and internal respirations can be seen in this illustration.
- Oxygen diffuses into the cells, while carbon dioxide mostly diffuses into the blood plasma. The diffusion in both types of respiration is based on Dalton's law of **partial pressures**.

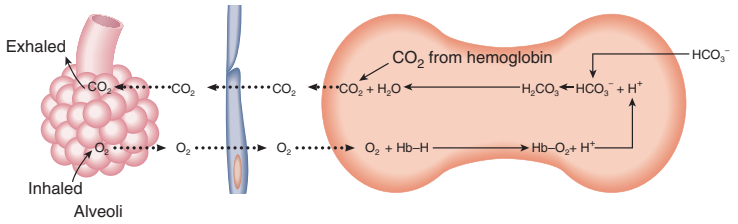
Figure 13.16



4 Transport of Oxygen and Carbon Dioxide Requires Hemoglobin and Plasma 362

- Oxygen is carried bound to iron in hemoglobin molecules in red blood cells.
- As shown here, most carbon dioxide is moved as **bicarbonate ions** in plasma. Bicarbonate also serves as a **buffer** that stabilizes pH in the blood. Some carbon dioxide is carried by the protein portion of hemoglobin, turning venous blood blue.

Figure 13.18



5 Respiratory Health Is Critical to Survival 365

- In constrictive respiratory diseases like asthma and bronchitis, airway diameter is reduced. Obstructive diseases, including emphysema, cystic fibrosis, tuberculosis, pneumonia, and lung cancer, and COPD as shown, involve physical obstructions to airflow.
- The death toll due to lung cancer in the United States is high, but the disease is preventable: smoking causes most cases.

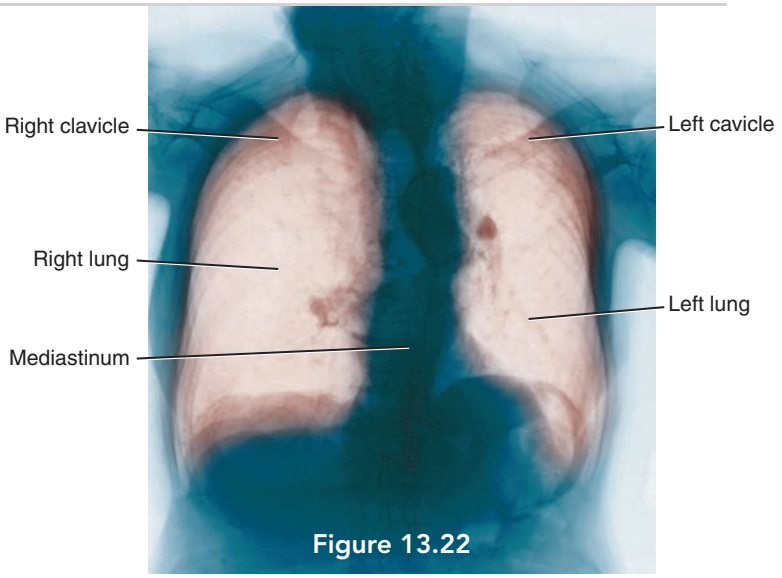


Figure 13.22

Key Terms

- acute sinusitis 365
- affinity 363
- bicarbonate ion 363
- buffer 363
- chemoreceptors 359
- chronic sinusitis 365
- hilum 353
- histamine 365
- larynx 346
- lower respiratory tract 346
- macrophage 351
- oxyhemoglobin 364
- partial pressure 361
- pharynx 346
- pleurisy 354
- respiratory membrane 349
- upper respiratory tract 346
- vocal folds 349

Critical and Creative Thinking Questions

1. We know humans cannot breathe under water, and yet fish can. One difference between fish gills and human lungs is that the blood in the gill flows in a countercurrent pattern. This means the water and blood flow across the respiratory surface in opposite directions. How might this speed oxygen removal from the water? Draw a schematic of this arrangement with arrows to show how countercurrent flow works. What else do humans lack for breathing under water? How might our physiology be "improved" to allow us to extract oxygen from water?
2. Although lung cancer is the most common cancer associated with smoking, the larynx is also susceptible to tobacco smoke. When cancer is detected in the larynx, the affected area is removed. What problems would you expect if the entire larynx was removed? Often, the tumors appear on the vocal folds. How might removal of these growths affect vocalization? What alternative methods of sound production might be available to victims of laryngeal cancer?

3. In Chapter 12, we discussed carbon monoxide poisoning. How would the physiology of the respiratory system change if red blood cells were saturated with CO? What might happen to the respiratory rate? To airway diameter? Death via CO poisoning occurs after the patient slips into unconsciousness. Physiologically, what is causing that unconsciousness?

4. Chapter 7 explained the sympathetic nervous system. How does activation of the fight-or-flight nervous system affect the respiratory system? What neurotransmitter is released, and how does it affect the functioning of the upper and lower respiratory tracts? What happens to pulmonary ventilation when the sympathetic nervous system is in control? Are there any changes in external or internal respiration?

5. **CLINICAL CLICK QUESTION**
Gregory was a healthy happy child of 12 when his family moved from the midwestern United States to Guam. Although uprooted from his friends, he was excited about the move and exhibited no emotional or social distress. After living there for three weeks, however, Gregory developed difficulty breathing. He would remark that his chest felt "too heavy to fill with air," and when running he often slowed down to hang his head and try to inhale deeply. This generally led to a dry hacking coughing fit. Gregory's mother noticed that he was making odd whistling noises as he tried to inhale, and his fingernails carried a pale bluish tint. Because she was a chronic asthmatic, Greg's mother had an albuterol inhaler available. In desperation she allowed Gregory to use it during one of his coughing attacks. His breathing was almost immediately restored. When Gregory went in for his yearly physical, the doctor diagnosed his condition as asthma. Why did Gregory's asthma appear at age 12 and not before? What might have triggered his breathing trouble? Why does asthma cause Gregory to feel that his chest is "too heavy?" For a look at the causes and symptoms of asthma, visit http://www.emedicinehealth.com/asthma/article_em.htm.

What is happening in this picture?

Have you ever been to the opera? It is awe inspiring. The singing is deep, beautiful, controlled, and impressively loud. Although the opera singer's anatomy is basically the same as everyone else's, the sounds he or she is able to produce are far superior. Through years of training, the singer is able to control breathing rate, airflow, and laryngeal tension to produce incredible notes. The musical capability of our respiratory system is quite astounding.

NATIONAL GEOGRAPHIC

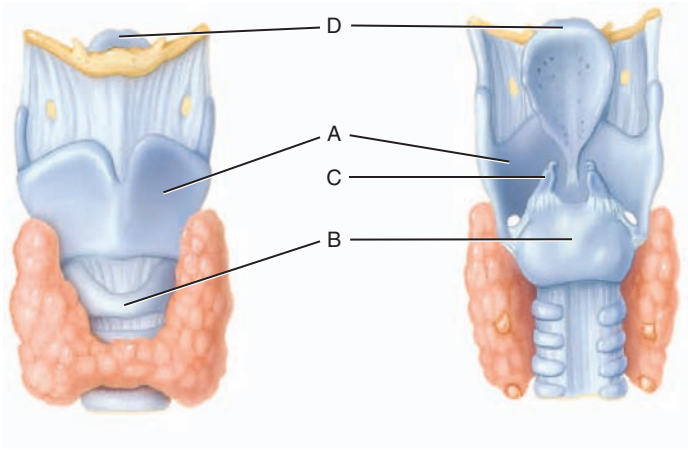
Think Critically

1. What muscles are involved in the deep inhalations and controlled and prolonged exhalations necessary to sing like this?
2. Which portions of the larynx are involved in the control of pitch?
3. How would you expect the lung capacities of this person to compare with your own?

Self-Test

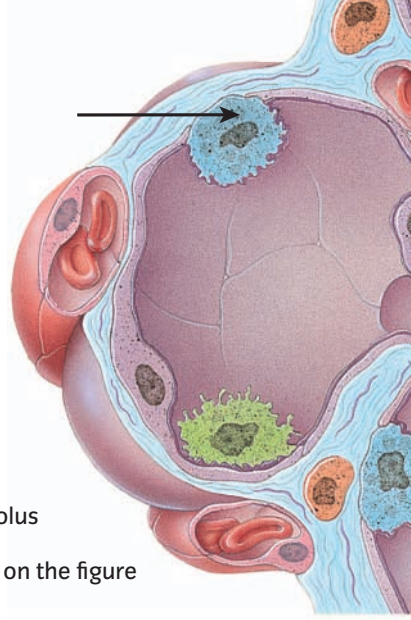
1. The function of the upper respiratory system is to _____.
   a. warm incoming air
   b. vocalize
   c. exchange gases with blood
   d. prevent lung infections

2. On the diagram, the cartilage that prevents food and liquids from entering the lower respiratory system is labeled _____.
   a. A
   b. B
   c. C
   d. D



3. The proper sequence of structures in the lower respiratory tract is _____.
   a. trachea, bronchioles, bronchi, respiratory bronchioles
   b. trachea, respiratory bronchioles, bronchioles, bronchi
   c. trachea, bronchi, bronchioles, respiratory bronchioles
   d. trachea, bronchi, respiratory bronchioles, bronchioles

4. A side effect of the respiratory tubes getting smaller and smaller is that _____.
   a. cartilage support lessens
   b. the proportion of smooth muscle increases
   c. the surface area of the respiratory system increases
   d. All of the above are correct.



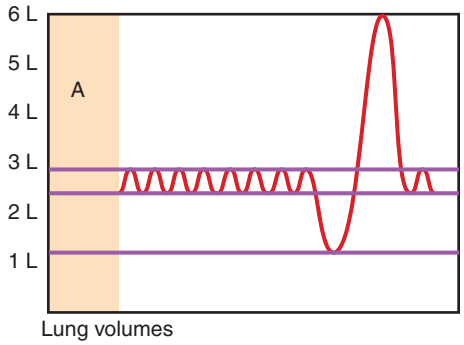
5. The function of the structure indicated by the arrow in the figure on the right is to _____.
   a. serve as a diffusion membrane for gases
   b. produce surfactant
   c. patrol the alveoli, removing debris and bacteria
   d. support the delicate walls of the alveolus

6. The function of the entire area depicted on the figure above is _____.
   a. diffusion of gases into and out of the blood
   b. infection fighting within the lungs
   c. movement of air into the deeper tissues of the respiratory system
   d. thermal homeostasis

7. During inspiration, the diaphragm _____, _____ the volume of the thoracic cavity.
   a. contracts/increasing
   b. contracts/decreasing
   c. relaxes/increasing
   d. relaxes/decreasing

8. The gas law that dictates the differential movement of carbon dioxide and oxygen into and out of the tissues of the body is Boyle's law.
   a. True
   b. False

9. The volume indicated as A on this diagram is the _____.
   a. vital capacity
   b. tidal volume
   c. expiratory reserve volume
   d. inspiratory reserve volume



10. The movement of oxygen from the blood into the tissues is referred to as _____.
    a. internal respiration
    b. external respiration
    c. Dalton's law

11. Carbon dioxide moves from the tissues of the body into the blood because _____.
    a. the partial pressure of oxygen is lower in the tissues
    b. the partial pressure of carbon dioxide is lower in the blood
    c. the volume of carbon dioxide decreases in the blood
    d. carbon dioxide floats in the blood and will always travel upward

12. Oxygen is carried on the _____.
    a. plasma proteins of the blood
    b. protein portion of the hemoglobin molecule
    c. iron portion of the hemoglobin molecule
    d. white blood cells

13. Hemoglobin binds oxygen more tightly when oxygen concentrations are _____ and pH is _____.
    a. low/low
    b. high/low
    c. high/high
    d. low/high

14. Bronchitis is an example of a constrictive disease.
    a. True
    b. False

15. Bacteria are responsible for causing _____.
    a. cystic fibrosis
    b. tuberculosis
    c. asthma
    d. emphysema

THE PLANNER

Review your Chapter Planner on the chapter opener and check off your completed work.

Nutrition: You Are What You Eat

Have you seen *Super Size Me*—the movie by the man who ate nothing but McDonald's food for one excruciating month? Part of the delicious delight of watching Morgan Spurlock work his way through endless Big Macs stems from pure contrariness. Your mother, after all, told you not to eat junk food, and here is Spurlock, gobbling like mad. The other delight comes from your mother's vindication. Sure enough, Spurlock suffers mightily for his excess.

Long ago, when the Beatles sang, "You know that what you eat, you are," the idea that food might affect health was revolutionary. Not anymore. Today, the idea that the food you consume can affect your health is commonplace. Indeed, many are surprised by a study that finds, for example, that eating less fat may not reduce the incidence of breast cancer or that calcium supplements may not ward off osteoporosis.

At the center of all this concern is nutrition. In an era of rising obesity in the developed world but tragically persistent starvation and undernourishment in many countries, the right to safe and nutritious food is always a critical issue. The goal of this chapter is to increase your nutritional literacy. The next chapter will discuss the digestive system—the organs and processes that convert food into simple compounds that the body can use to build and maintain cells and tissues.

Chapter Outline

Nutrients Are Life Sustaining 378

- There Are Three Classes of Macronutrients
- MyPyramid Is a Dietary Guideline
- Vitamins and Minerals Are Micronutrients

Nutrients Are Metabolized 390

- Carbohydrate Metabolism Can Release Energy Gradually
- Lipid Metabolism Is Another Source of Energy
- Protein Metabolism Is Also Important to Good Health
- Energy Input Should Match Energy Output

Health Can Be Hurt by Nutritional Disorders 394

- Food Is Life Sustaining, but Sometimes It Can Be Life Threatening
- Food Shortages Cause Other Nutrition-Related Problems

CHAPTER PLANNER

- ❑ Study the picture and read the opening story.
- ❑ Scan the Learning Objectives in each section:
  p. 378 ❑ p. 390 ❑ p. 394 ❑
- ❑ Read the text and study all figures and visuals. Answer any questions.

Analyze key features

- ❑ Biological InSight, p. 380
- ❑ I Wonder..., p. 385
- ❑ Process Diagram, p. 391
- ❑ Ethics and Issues, p. 395
- ❑ What a Scientist Sees, p. 396
- ❑ Health, Wellness, and Disease, p. 398
- ❑ Stop: Answer the Concept Checks before you go on:
  p. 389 ❑ p. 393 ❑ p. 398 ❑

End of chapter

- ❑ Review the Summary and Key Terms.
- ❑ Answer the Critical and Creative Thinking Questions.
- ❑ Answer What is happening in this picture?
- ❑ Answer the Self-Test Questions.

14.1 Nutrients Are Life Sustaining

LEARNING OBJECTIVES

1. **Differentiate** between macronutrients and micronutrients.
2. **Describe** how nutrients enter cells.
3. **Explain** how My Pyramid helps in making informed dietary choices.

All **aerobic** cells, and therefore all humans, need oxygen to survive. Oxygen drives the use of energy at the cellular level by serving as the ultimate electron "pull," creating the hydrogen ion concentration gradient required to form ATP. However, one cannot live by oxygen alone!

aerobic Requiring oxygen to metabolize.

nutrients Ingredients in food that are required by the body.

The cells of our body require **nutrients** in usable form to maintain homeostasis and create ATP. Because we are heterotrophs (see Chapter 2), we cannot manufacture our own organic compounds, so we must obtain them from the environment. Consequently, we spend a great deal of our time locating, preparing, and ingesting food.

Eating is so important that virtually every culture has elaborate rituals surrounding food. Think of your last Thanksgiving celebration, or even your birthday. Both of these events traditionally include a specific celebratory food: turkey with all the trimmings, or a cake with candles. In both cases, there are rituals surrounding the food. We take a moment to reflect on all the good things in our lives before eating Thanksgiving dinner, and we sing "Happy Birthday" and blow out candles before cutting the birthday cake.

Although we may not understand why, we intuitively know that we need nutrients in order to survive. What exactly are nutrients? A nutrient is defined as any compound required by the body. The two main types of nutrients are **macronutrients** (carbohydrates, lipids, and proteins) and **micronutrients** (vitamins and minerals). Both types describe organic and inorganic compounds that the body obtains from food rather than synthesizing itself. We ingest carbohydrates, lipids, and proteins to provide the necessary energy and materials for the body to create its own carbohydrates, lipids, and proteins. From these macronutrients, the body synthesizes cellular components, such as the cell membrane, enzymes, organelles, and even entirely new cells during cell division. We require micronutrients for the proper functioning of essential compounds, such as the enzymes of cellular respiration. Review Chapter 3 to refresh your understanding of carbohydrates, lipids, and proteins.

It is important to note that we take part in **nutrient cycling**, the flow of nutrients from our environment to us and back again to our environment. Bacteria and fungi play a crucial role in breaking down large organic molecules into small ones so our waste can be reused in the soil and reabsorbed by plants.

There Are Three Classes of Macronutrients

The average supermarket contains more than 20,000 food products, some of which are seen in **Figure 14.1**, but these all come down to three macronutrient groups: carbohydrates, fats, and proteins. These groupings are distinct from the six major food groups—grains, vegetables,

Three macronutrients packaged in thousands of ways • Figure 14.1

The supermarket is a marvel of macronutrient inventory management and delivery. However, some argue that supermarkets should be organized differently, and should move from a functional organization (coffee in "beverages" and cornflakes in "cereals") to a consumer organization—coffee and cornflakes in a "breakfast" section—or even a nutritional organization using food groups as the base.

fruits, milk, meat/beans, and oils—which are classified by food type rather than by their biochemical makeup (food groups are discussed later in the chapter). For example, fruits, a food group, provide us with carbohydrates in the form of fructose, and meats, another food group, are rich in protein.

Carbohydrates are our best source of energy.

One macronutrient that we often hear about in diet discussions is **carbohydrates**, and for good reason. Carbohydrates are our most efficient source of energy, meaning that when we digest carbohydrates we are left with nothing but energy, water, and carbon dioxide. With carbohydrates there are no difficult waste compounds to dispose of! Carbohydrates are composed of carbon, hydrogen, and oxygen in a 1:2:1 ratio and are in their simplest form merely carbon (*carbo*) plus water (*hydrate*). The most common carbohydrate, glucose, has the chemical formula $C_6H_{12}O_6$. Our cells are excellent at breaking down glucose to produce ATP or synthesize amino acids, glycogen, or triglycerides. Carbohydrate digestion is so efficient that we can ingest glucose and break it down completely into energy, carbon dioxide, and water. This reaction is summarized in **Figure 14.2**. Although our bodies are efficient carbohydrate-burning machines, some fad diets encourage us to avoid this energy source.

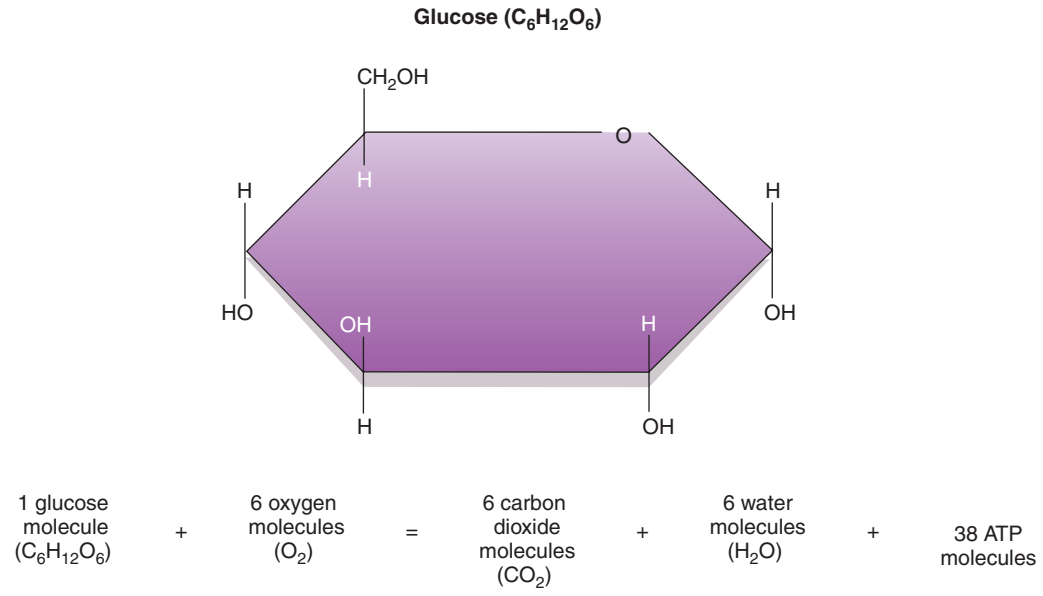
Lipids are another class of macronutrient.

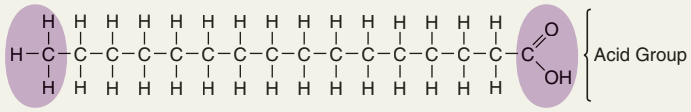
Lipids—fats—are a second class of macronutrient. Fats are long chains of carbon molecules, but they have many more carbon atoms and far fewer oxygen atoms than do carbohydrates.

Fats can be either **saturated**, meaning that every space in the carbon chain is occupied with hydrogens, or **unsaturated**, meaning that there are one or more double bonds in the carbon chain, as shown in **Figure 14.3** on the following page. In the case of unsaturated fat, if one double bond is present, the fat is termed *monounsaturated;* if the fat has more than one double bond, it is *polyunsaturated*. Because double bonds make kinks in the long carbon chains, unsaturated fats cannot pack together tightly. Unsaturated fats, including vegetable oils, are liquid at room temperature. Saturated fats are solid at room temperature and are usually derived from animals.

We need a little fat in our diet; however, most of us consume more than we need because fats of various kinds are added to many foods. Fats carry flavor and add texture to food. According to marketing tests, they coat the mouth and provide much-craved oral gratification. However, the American Cancer Society reports that diets high in fat can increase the incidence of cancer; accordingly, it has developed a set of recommendations for minimizing fat intake.

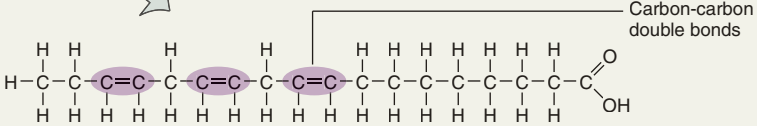
Structure of glucose and digestion reaction • Figure 14.2





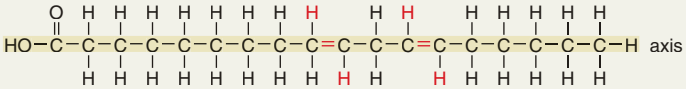
Saturated fatty acid: palmitic acid

Meats, butter, milk, and cheese are examples of foods rich in saturated fats.

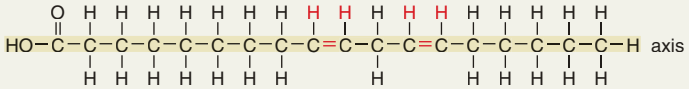


Polyunsaturated fatty acid: alpha-linoleic acid (omega-3)

Synthetic margarine is an example of a polyunsaturated fat that can be created as a trans fat or a cis fat.
Cis fats have the hydrogens on the same side of the main chain, whereas trans fats have one hydrogen above the chain and the other below.



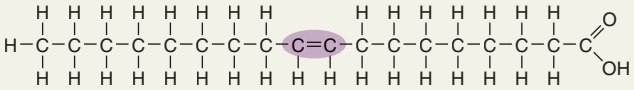
Linoleic acid: *trans* configuration (*trans* isomer)



Linoleic acid: *cis* configuration (*cis* isomer)

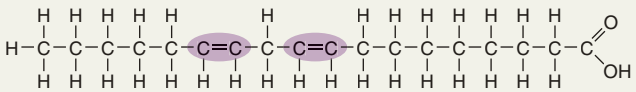
NATIONAL GEOGRAPHIC

Most animal products contain saturated fats, particularly those from beef and lamb. Most plants produce unsaturated fats, the notable exceptions being coconuts, cocoa butter, and palm kernel oils. For this reason, vegetable oil is liquid at room temperature, whereas butter and cocoa butter are solid.



Monounsaturated fatty acid: oleic acid (omega-9)

Olive oil and sunflower seeds contain monounsaturated fats. These occur as oils at room temperature.



Polyunsaturated fatty acid: linoleic acid (omega-6)

Walnuts and canola oils are both polyunsaturated fats with only two double bonds.

These are listed in Table 14.1. High-fat diets are high in **calories**, leading to obesity, which is associated with increased cancer risk. Saturated fats may increase cancer risk, whereas other fats, such as **omega-3** fats from fish oils, may reduce the risk of cancer.

calorie A measure of the amount of heat stored in food. One Calorie is the amount of heat needed to raise the temperature of 1 kilogram of water 1 degree Celsius.

Because fats are not soluble in water, they are not readily transported through our watery blood. They therefore combine with protein to form a **lipoprotein**, as shown in Figure 14.4. The lipids are "coated" with proteins, phospholipids (see Chapter 3), and cholesterol. Recall that phospholipids are polar at their phosphate end, allowing the molecule to be suspended in an aqueous environment. The technical term for molecules with both a hydrophylic end and a hydrophobic end is *amphipathic*. Low-density lipoproteins (LDLs) contain 25% protein, 20% phospholipids, 45% cholesterol, and 10% other lipids. LDLs carry most of the cholesterol in our blood and can deposit it in and around the smooth muscle fibers in arteries. This process forms fatty plaques that increase the risk of coronary artery disease. Hence, the cholesterol found in LDLs is called "bad" cholesterol. High-density lipoproteins (HDLs), on the other hand, contain about 45% protein, 30% phospholipids, and only about

Good and bad fats Table 14.1

To limit your intake of cholesterol, *trans* fat, and saturated fat:

- Trim the fat from your steak and roast beef.
- Serve chicken and fish, but don't eat the skin.
- Try a vegetarian meal once a week.
- Limit your eggs to one or two a week.
- Choose low-fat milk and yogurt.
- Use half your usual amount of butter or margarine.
- Have only a small order of fries, or share them with a friend.

To increase your intake of polyunsaturated and monounsaturated fats:

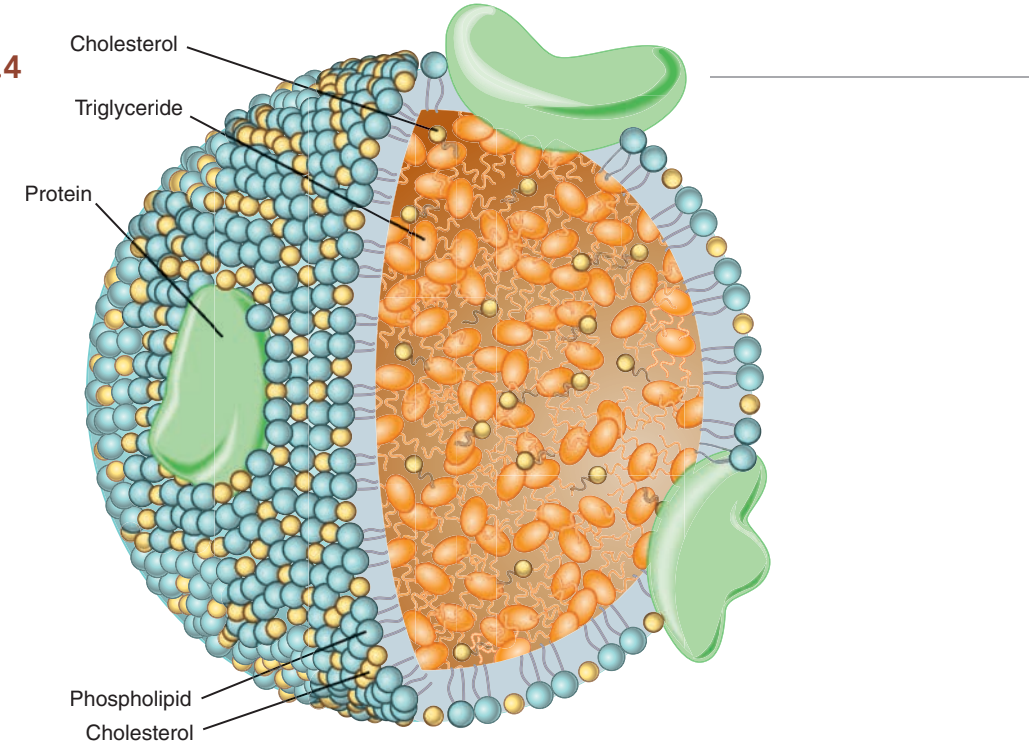
- Use olive, peanut, or canola oil for cooking and salad dressing.
- Use corn, sunflower, or safflower oil for baking.
- Snack on nuts and seeds.
- Add olives and avocados to your salad.

To increase your omega-3 intake:

- Sprinkle flax seed on your cereal or yogurt.
- Add another serving of fish to your weekly menu.
- Have a leafy green vegetable with dinner.
- Add walnuts to your cereal.

A lipoprotein • Figure 14.4

As the name suggests, lipoproteins are composed of a lipid attached to a protein. The relative size of each component determines the density of the lipoprotein: A higher percentage of lipid equals lower density lipoprotein.



Essential and nonessential amino acids Table 14.2a

Essential amino acids	Nonessential amino acids
Isoleucine	Alanine
Leucine	Arginine*
Lysine	Asparagine
Methionine	Aspartic acid (aspartate)
Phenylalanine	Cysteine (cystine)*
Threonine	Glutamic acid (glutamate)
Tryptophan	Glutamine*
Valine	Glycine*
Histidine*	Proline*
	Serine
	Tyrosine*

*The Institute of Medicine, Food and Nutrition Board classifies these amino acids as "conditionally essential" (*Dietary Reference Intakes for Energy, Carbohydrates, Fiber, Fat, Protein and Amino Acids*. Washington, DC: National Academy Press, 2002).

Complementary proteins Table 14.2b

Rice and beans
Rice and lentils
Bread with peanut butter
Tofu and cashew stir-fry
Bean burrito in corn tortilla
Hummus (chickpeas and sesame seeds)
Black-eyed peas and corn bread
Tahini (sesame seeds) and peanut sauce
Trail mix (soybeans and nuts)
Rice and tofu

25% cholesterol and other lipids. With the lower percentage of cholesterol, HDLs are called "good" cholesterol. They are considered good because HDL removes excess cholesterol from the arterial wall and transports it to the liver for disposal or use.

Proteins are an essential part of our diet. The last class of macronutrients is **protein**. Proteins are an essential part of our diet because the amino acids they contain are not stored in the body. Instead of completely breaking down the amino acids of ingested proteins for energy, the body usually recycles them into proteins of its own. Of the 20 amino acids that make up living organisms, we can manufacture only 11. The remaining **essential amino acids** must come from our diet, as seen in Table 14.2a. Obtaining these amino acids is a problem only for people who choose not to consume red meat.

Complete proteins, such as those found in red meat and fish, contain all 20 amino acids. Unlike meat, no single vegetable or fruit contains all nine of the essential amino acids. For those who choose to restrict their meat intake, however, eating legumes and grains, or combining cereal with milk, will provide a full complement of amino acids. **Vegans** and vegetarians can be quite healthy, assuming that they monitor their protein intake. See Table 14.2b for a list of food combinations that contain complementary amino acids.

vegan A vegetarian who consumes only plant products, eating no animal products whatsoever.

MyPyramid Is a Dietary Guideline

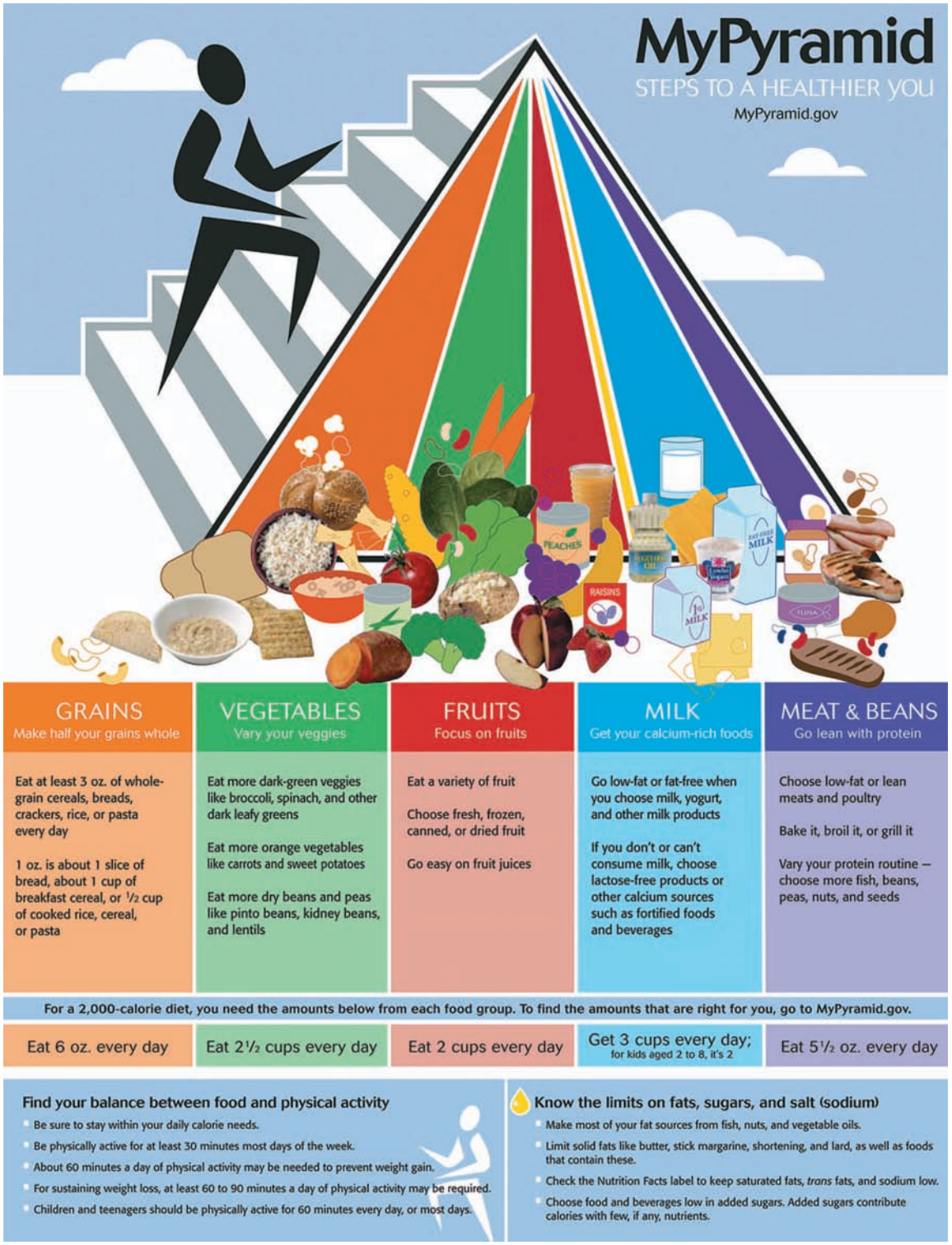
Food groups are not nutrient classes. Rather, they are the major categories of foods: meats, dairy products, breads and pastas, vegetables, and oils or fats. Each group is important to overall health, and the recommended daily caloric intake for each group differs. For example, the recommended daily allowance (RDA) for meats is quite low, at two servings per day, or 50 grams for women and 63 for men. Most Americans consume far more than that. A "regular" hamburger from any fast-food establishment usually provides approximately 28 g of protein, so a typical "double" cheeseburger provides the entire daily protein requirement for an adult woman.

You may be familiar with the traditional **food guide pyramid**, which suggested healthy proportions of the food groups, based on the eating habits of healthy people in the United States and around the world. The pyramid offered guidelines for the number of servings of each type of food that should be eaten each day. At the bottom of the pyramid were breads, cereals, and pastas, with a recommended 6 to 11 servings per day. Fruits and vegetables were next, with a recommended 3 to 5 servings of each daily. Milk and cheese and proteins and beans constituted the next level, at 2 to 3 servings of each a day. At the top of the pyramid were fats, with a recommendation that they be used "sparingly."

The U.S. Department of Agriculture recently updated its food pyramid with MyPyramid, which can be found online at http://www.mypyramid.gov. (See **Figure 14.5**.) Although this pyramid is more in tune with current research, it is based on the same principles as the traditional pyramid. It still recommends that we get most of our caloric value from carbohydrates and limit our fat intake. Rather than being arranged horizontally, however, the food groups are

MyPyramid • Figure 14.5

It is important to note that carbohydrates remain our best source of energy.



arranged vertically. This provides a more accurate visual picture, because we require all the food groups in order to be healthy. The MyPyramid Web site is more personalized than earlier versions, giving recommendations for serving size and number based on age, gender, and activity level. When you submit your personal statistics, you receive food intake guidelines that are matched to your lifestyle, along with suggestions for improving your choices within each group. The suggested amount of whole grains is listed as a portion of the carbohydrates, and the vegetable group is divided into dark greens, orange vegetables, dry beans and peas, starchy vegetables, and others. Although this is by no means an exhaustive view of good eating, it provides a starting point for making healthier choices.

The MyPyramid graphic encourages moderation and variety. It also has a very small, uncolored section at the top for "discretionary" calories, such as those provided by candy and alcohol. It is worth noting that other organizations have produced different guidelines, created with the cultural and eating habits of other groups in mind. For example, the World Health Organization has a guideline that suggests eating about half the amount of fruits and vegetables recommended by MyPyramid. All of these guidelines are designed to help you maintain ideal body weight. See *I Wonder… How Is My Ideal Body Weight Determined?* for more on the concept of ideal body weight.

Vitamins and Minerals Are Micronutrients

A healthy diet must include vitamins and minerals. Unlike macronutrients, these micronutrients are not broken down but instead are used intact and are required for enzyme functioning or the synthesis of specific proteins. Vitamins are organic substances, such as thiamine, riboflavin, and vitamin A (see **Table 14.3** on the following page). Minerals are inorganic substances, such as calcium, zinc, and iodine (see **Table 14.4** on pages 388–389).

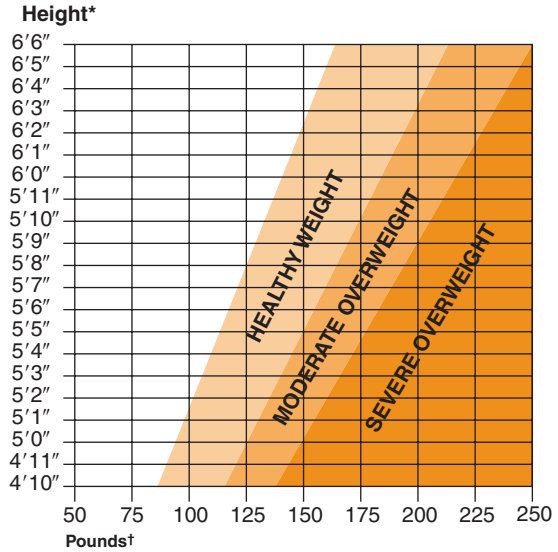
I WONDER...

How Is My Ideal Body Weight Determined?

When you go to a physician for your annual physical, one of the first measurements taken is your weight. This, along with your height, is entered on your chart for the physician to review. During the interview that follows, your physician may talk to you about your weight, perhaps suggesting that you drop a few pounds or even pick up a little weight.

What is the standard from which these recommendations stem? Interestingly, medical professionals do not themselves evaluate data on weight and corresponding health issues. Instead, insurance companies keep close tabs on the relationship between the two. Each company keeps its own records indicating the relationship between their clients' weight and the amount of money that client has cost them in health-related expenses. Over time, these companies build up an impressive data bank of weight and health-care correlations. Of course, this is nothing more than a business plan. Nevertheless, medical professionals use these weight and health statistics when reviewing patient data and often counsel their patients to remain within what the insurance companies deem a healthy weight range.

Another type of healthy body size calculation involves determining your body mass index (BMI). This is based on the ratio between your weight and height but does not take into account factors such as muscular development or bone mass. BMI is often used in diagnosing and tracking obesity, and is discussed further later in this chapter.



* Without shoes

† Without clothes. The higher weights apply to people with more muscle and bone, such as many men.

Vitamins Table 14.3

Vitamins	Comment and Source	Functions	Deficiency symptoms and disorders
Fat-soluble	All require bile salts and some dietary lipids for adequate absorption.		
A	Formed from provitamin beta-carotene (and other provitamins) in GI tract. Stored in liver. Sources of carotene and other provitamins include orange, yellow, and green vegetables. ***Dietary sources*** of vitamin A include liver and milk.	Maintains general health and vigor of epithelial cells. Beta-carotene acts as an antioxidant to inactivate free radicals. Essential for formation of light-sensitive pigments in photoreceptors of retina. Aids in growth of bones and teeth by helping to regulate activity of osteoblasts and osteoclasts.	Deficiency results in dry skin and hair; increased incidence of ear, sinus, respiratory, urinary, and digestive system infections; inability to gain weight; drying of cornea; and skin sores. **Night blindness** or decreased ability for dark adaptation. Slow and faulty development of bones and teeth.
D	Sunlight converts 7-dehydrocholesterol in the skin to cholecalciferol (vitamin D_3). A liver enzyme then converts cholecalciferol to 25-hydroxycholecalciferol. A second enzyme in the kidneys converts 25-hydroxycholecalciferol to the active form of vitamin D. ***Dietary sources*** include fish-liver oils, egg yolk, and fortified milk.	Essential for absorption of calcium and phosphorus from GI tract. Works with parathyroid hormone (PTH) to maintain Ca^{2+} homeostasis.	Defective utilization of calcium by bones leads to **rickets** in children and **osteomalacia** (softened bones) in adults. Possible loss of muscle tone.
E (tocopherols)	Stored in liver, adipose tissue, and muscles. ***Dietary sources*** include fresh nuts and wheat germ, seed oils, and green leafy vegetables.	Inhibits breakdown of certain fatty acids that help form cell structures. Involved in formation of DNA, RNA, and red blood cells. May promote wound healing, contribute to normal structure and functioning of the nervous system, and prevent scarring. May help protect liver from toxic chemicals. Acts as an antioxidant to inactivate free radicals.	May cause oxidation of monounsaturated fats, resulting in abnormal structure and function of mitochondria, lysosomes, and plasma membranes. A possible consequence is hemolytic anemia.
K	Produced by intestinal bacteria. Stored in liver and spleen. ***Dietary sources*** include spinach, cauliflower, cabbage, and liver.	Coenzyme essential for synthesis of several clotting factors.	Delayed clotting time results in excessive bleeding.
Water-soluble	Dissolved in body fluids. Most are not stored in body. Excess intake is eliminated in urine.		
B_1 (thiamine)	Rapidly destroyed by heat. ***Dietary sources*** include whole-grain products, eggs, pork, nuts, liver, and yeast.	Acts as coenzyme for many different enzymes that break carbon-to-carbon bonds and are involved in carbohydrate metabolism. Essential for synthesis of the neurotransmitter acetylcholine.	Improper carbohydrate metabolism leads to buildup of pyruvate and lactic acids and insufficient production of ATP for muscle and nerve cells. Deficiency leads to: (1) **beriberi,** partial paralysis of smooth muscle of GI tract, causing digestive disturbances; skeletal muscle paralysis; and atrophy of limbs; (2) **polyneuritis**, due to degeneration of myelin sheaths; impaired reflexes, impaired sense of touch, stunted growth in children, and poor appetite.

Vitamins	Comment and Source	Functions	Deficiency symptoms and disorders
B_2 (riboflavin)	Small amounts supplied by bacteria of GI tract. ***Dietary sources*** include yeast, liver, beef, veal, lamb, eggs, whole-grain products, asparagus, peas, beets, and peanuts.	Component of certain coenzymes (for example, FAD) in carbohydrate and protein metabolism, especially in cells of eye, skin, intestine, and blood.	Deficiency may lead to improper utilization of oxygen resulting in blurred vision, cataracts, and corneal ulcerations. Also dermatitis and cracking of skin, lesions of intestinal mucosa, and one type of anemia.
Niacin (nicotinamide)	Derived from amino acid tryptophan. ***Dietary sources*** include yeast, meats, liver, fish, whole-grain products, peas, beans, and nuts.	Essential component of NAD and NADP, coenzymes in oxidation-reduction reactions. In lipid metabolism, inhibits production of cholesterol and assists in triglyceride breakdown.	Principal deficiency is **pellagra**, characterized by dermatitis, diarrhea, and psychological disturbances.
B_6 (pyridoxine)	Synthesized by bacteria of GI tract. Stored in liver, muscle, and brain. ***Dietary sources*** include salmon, yeast, tomatoes, yellow corn, spinach, whole-grain products, liver, and yogurt.	Essential coenzyme for normal amino acid metabolism. Assists production of circulating antibodies. May function as coenzyme in triglyceride metabolism.	Most common deficiency symptom is dermatitis of eyes, nose, and mouth. Other symptoms are retarded growth and nausea.
B_{12} (cyanocobalamin)	Only B vitamin not found in vegetables; only vitamin containing cobalt. Absorption from GI tract depends on intrinsic factor secreted by stomach mucosa. ***Dietary sources*** include liver, kidney, milk, eggs, cheese, and meat.	Coenzyme necessary for red blood cell formation, formation of the amino acid methionine, entrance of some amino acids into Krebs cycle, and manufacture of choline (used to synthesize acetylcholine).	**Pernicious anemia**, neuropsychiatric abnormalities (ataxia, memory loss, weakness, personality and mood changes, and abnormal sensations), and impaired activity of osteoblasts.
Pantothenic acid	Some produced by bacteria of GI tract. Stored primarily in liver and kidneys. ***Dietary sources*** include kidney, liver, yeast, green vegetables, and cereal.	Constituent of coenzyme A, which is essential for transfer of acetyl group from pyruvic acid into the Krebs cycle, conversion of lipids and amino acids into glucose, and synthesis of cholesterol and steroid hormones.	Fatigue, muscle spasms, insufficient production of adrenal steroid hormones, vomiting, and insomnia.
Folic acid (folate, folacin)	Synthesized by bacteria of GI tract. ***Dietary sources*** include green leafy vegetables, broccoli, asparagus, breads, dried beans, and citrus fruits.	Component of enzyme systems synthesizing nitrogenous bases of DNA and RNA. Essential for normal production of red and white blood cells.	Production of abnormally large red blood cells (**macrocytic anemia**). Higher risk of neural tube defects in babies born to folate-deficient mothers.
Biotin	Synthesized by bacteria of GI tract. ***Dietary sources*** include yeast, liver, egg yolk, and kidneys.	Essential coenzyme for carbohydrate metabolism and synthesis of fatty acids and purines.	Mental depression, muscular pain, dermatitis, fatigue, and nausea.
C (ascorbic acid)	Rapidly destroyed by heat. Some stored in glandular tissue and plasma. Dietary sources include citrus fruits, tomatoes, and green vegetables.	Promotes protein synthesis. As coenzyme, may combine with poisons, rendering them harmless until excreted. Works with antibodies, promotes wound healing, and functions as an antioxidant.	**Scurvy;** anemia; many symptoms related to poor collagen formation, including tender swollen gums, loosening of teeth, poor wound healing, bleeding, and retardation of growth.

Minerals Table 14.4

Mineral	Comments and sources	Importance
Calcium	Most abundant mineral in body. Appears in combination with phosphates. About 99% is stored in bones and teeth. Blood Ca^{2+} level is controlled by parathyroid hormone (PTH). Calcitriol promotes absorption of dietary calcium. ***Dietary sources*** are milk, egg yolk, shellfish, and leafy green vegetables.	Formation of bones and teeth, blood clotting, normal muscle and nerve activity, endocytosis and exocytosis, cellular motility, chromosome movement during cell division, glycogen metabolism, and release of neurotransmitters and hormones.
Phosphorus	About 80% is found in bones and teeth as phosphate salts. Blood phosphate level is controlled by parathyroid hormone (PTH). ***Dietary sources*** are dairy products, meat, fish, poultry, and nuts.	Formation of bones and teeth. Phosphates ($H_2PO_4^-$, HPO_4^- and PO_4^{3-}) constitute a major buffer system of blood. Plays important role in muscle contraction and nerve activity. Component of many enzymes. Involved in energy transfer (ATP). Component of DNA and RNA.
Potassium	Major cation (K^+) in intracellular fluid. Present in most foods (meats, fish, poultry, fruits, and nuts).	Needed for formation and conduction of action potentials in neurons and muscle fibers.
Sulfur	Component of many proteins, electron carriers in electron transport chain, and some vitamins (thiamine and biotin). ***Dietary sources*** include beef, liver, lamb, fish, poultry, eggs, cheese, and beans.	As component of hormones and vitamins, regulates various body activities. Needed for ATP production by electron transport chain.
Sodium	Most abundant cation (Na^+) in extracellular fluids; some found in bones. Normal intake of NaCl (***table salt***) supplies more than the required amounts.	Strongly affects distribution of water through osmosis. Part of bicarbonate buffer system. Functions in nerve and muscle action potential conduction.
Chloride	Major anion (Cl^-) in extracellular fluid. ***Dietary sources*** include table salt (NaCl), soy sauce, and processed foods.	Plays role in acid–base balance of blood, water balance, and formation of HCl in stomach.
Magnesium	Important cation (Mg^{2+}) in intracellular fluid. ***Widespread*** in various foods, such as green leafy vegetables, seafood, and whole-grain cereals.	Required for normal functioning of muscle and nervous tissue. Participates in bone formation. Constituent of many coenzymes.
Iron	About 66% found in hemoglobin of blood. ***Dietary sources*** are meat, liver, shellfish, egg yolk, beans, legumes, dried fruits, nuts, and cereals.	As component of hemoglobin, reversibly binds O_2. Component of cytochromes involved in electron transport chain.
Iodine	Essential component of thyroid hormones. ***Dietary sources*** are seafood, iodized salt, and vegetables grown in iodine-rich soils.	Required by thyroid gland to synthesize thyroid hormones, which regulate metabolic rate.
Manganese	Some stored in liver and spleen.	Activates several enzymes. Needed for hemoglobin synthesis, urea formation, growth, reproduction, lactation, bone formation, and possibly production and release of insulin and inhibition of cell damage.
Copper	Some stored in liver and spleen. ***Sources*** include eggs, whole-wheat flour, beans, beets, liver, fish, spinach, and asparagus.	Required with iron for synthesis of hemoglobin. Component of coenzymes in electron transport chain and enzyme necessary for melanin formation.
Cobalt	Constituent of vitamin B_{12}.	As part of vitamin B_{12}, required for red blood cell formation.

Mineral	Comments and sources	Importance
Zinc	Important component of certain enzymes. ***Widespread*** in many foods, especially meats.	Important in enzyme-driven metabolism. Necessary for normal growth and wound healing, normal taste sensations and appetite, and normal sperm counts in males. Involved in protein digestion.
Fluoride	Components of bones, teeth, other tissues.	Appears to improve tooth structure and inhibit tooth decay.
Selenium	Important component of certain enzymes. ***Dietary sources*** are seafood, meat, chicken, tomatoes, egg yolk, milk, mushrooms, garlic, and cereal grains grown in selenium-rich soil.	Needed for synthesis of thyroid hormones, sperm motility, and proper functioning of the immune system. Also functions as an antioxidant. Prevents chromosome breakage and may play a role in preventing certain birth defects, miscarriage, prostate cancer, and coronary artery disease.
Chromium	***Found in*** high concentrations in brewer's yeast. Also found in wine and some brands of beer.	Needed for normal activity of insulin in carbohydrate and lipid metabolism.

A healthy diet with plenty of fruit and vegetables will give you most of the necessary vitamins and minerals. However, many Americans now supplement their diets with moderate amounts of vitamins and minerals, just to ensure that they receive what they need on a daily basis. The usual supplement taken is an over-the-counter (OTC) multivitamin supplement. The typical ingredient list on an OTC daily multivitamin supplement includes most of what is found in Tables 14.3 and 14.4. These supplements often include vitamins E, C, and A, which help remove free radicals, thereby boosting the immune system and perhaps prolonging cell life. As with anything, excess is not healthy. Taking too large a quantity of fat-soluble vitamins can cause them to build up in the liver, hampering its functioning.

OTC vitamins usually also contain selected minerals, such as calcium, phosphorus, iodine, magnesium, and zinc, among many other micronutrients. Some minerals are found in high concentration in foods, especially prepared foods. Sodium, for example, is extremely high in most frozen and prepared foods. Because the general population consumes a large quantity of these convenience foods, sodium supplements are seldom advisable. Too much sodium in the diet may lead to hypertension.

By eating mostly whole grains, we obtain vitamins and minerals as well as glucose. Whole grain also provides **fiber**, which helps move feces along the large intestine and decreases the risk of colon cancer. **Milled** grains lose their fibrous, mineral-rich outer husk, diminishing their nutritional value. Simple carbohydrates, such as sucrose, usually provide energy and nothing else. These are sometimes called "empty calories," because they contribute more to weight gain than to homeostasis.

milled Ground, as in grain that has been ground into flour.

CONCEPT CHECK

1. **What** type of nutrient is vitamin B? Is starch, a polymer of sugar, considered a macronutrient or a micronutrient?
2. **How** do nutrients enter the cell?
3. **What** personalized dietary information can be obtained from MyPyramid?

14.2 Nutrients Are Metabolized

LEARNING OBJECTIVES

1. **List** the steps of carbohydrate metabolism.
2. **Define** the difference between lipid and protein metabolism.
3. **Describe** the factors that determine how much energy our bodies expend.

The nutrients we take in must be put to work. The term **metabolism** refers to the chemical reactions in cells that break down and build up nutrients. There are two basic kinds of metabolic reactions. One kind combines molecules into more complex compounds, consuming more energy than it produces. This kind is an **anabolic** reaction. The other kind of reaction breaks molecules down, producing more energy than it consumes. This type is a **catabolic** reaction. Carbohydrates, lipids, and proteins all undergo both anabolic and catabolic reactions.

metabolism The chemical reactions that take place in the body.

chemiosmosis The diffusion of hydrogen ions across a membrane, generating ATP as the ions move from high to low concentrations.

Carbohydrate Metabolism Can Release Energy Gradually

Carbohydrate catabolism, or cellular respiration, is actually a controlled burning of the glucose molecule through a series of enzymatic reactions that take place in our cells. Although humans do not spontaneously combust, we do release the energy in foods through a process that involves sequentially breaking chemical bonds. Burning releases energy all at once, whereas carbohydrate metabolism releases energy gradually.

The first reaction is **glycolysis**, which converts one glucose molecule into two **pyruvate** molecules, releasing a small amount of energy. Assuming that oxygen is present, the pyruvates are then passed along to a mitochondrion in the cytoplasm of the cell, where oxidation continues. The mitochondrion completes the enzymatic burning of glucose by passing the compounds through the **Krebs cycle**, in which energy-rich compounds are created, and then passing these compounds through the **electron transport chain**. These steps produce the carbon dioxide that we exhale.

glycolysis The enzymatic breakdown of glucose into pyruvate, occurring within the cytoplasm.

Chemiosmosis within the inner membrane of the mitochondrion produces most of the ATP used by cells. Carbohydrate metabolism is seen in Figure 14.6.

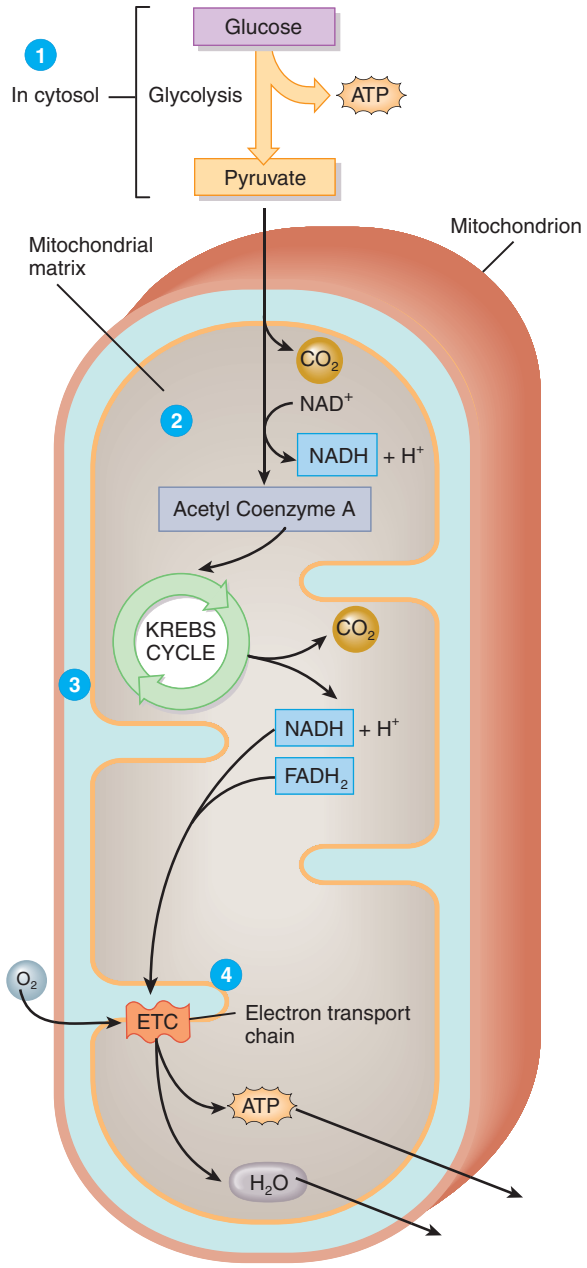
Most of the glucose in our bodies is catabolized (broken down) to make ATP, but glucose can also be formed through anabolic reactions. Many glucose molecules combine to form *glycogen*, the only carbohydrate that is stored in our bodies—in the liver and skeletal muscles. The hormone *insulin* is a key to the synthesis of glycogen, a process called **glycogenesis**. There is a limit, however, to how much glycogen we can make and store. Intense athletic events such as running a marathon may completely exhaust the body's supply of glycogen, and that is why many athletes eat plenty of carbohydrates in the days before their events—a practice called "carbohydrate loading." The idea is to "load" the muscles with the maximum possible amount of stored glycogen so that energy will be readily available on the day of the race.

Lipid Metabolism Is Another Source of Energy

Lipids, like carbohydrates, can be oxidized to produce ATP. If the body lacks carbohydrates, the normal source for glucose needed to produce ATP, it mobilizes fat stores and converts fat into small molecules called *ketones*. As ketones are oxidized to produce ATP, their concentration in the blood can rise above normal levels, and the body may enter a metabolic state called **ketosis**. Extreme ketosis can lead to **acidosis**, in which the pH of blood becomes very low (acidic). Acidosis is serious—it can lead to a coma or even death. A sign that a diabetic individual is critically low on insulin is sweet-smelling breath, caused by a ketone, *acetone*, diffusing from the pulmonary capillaries into the person's exhalations.

Glycolysis, the Krebs cycle, and electron transport • Figure 14.6

Glycolysis occurs in the cytoplasm, requiring two molecules of ATP to begin, but generating a total of four ATP molecules in the conversion of one molecule of glucose into two molecules of pyruvate. With oxygen present, the two pyruvate molecules are shuttled to the mitochondrion, where they are passed through a series of chemical reactions in which each step releases energy that is harvested in ATP, NADH, and $FADH_2$. These reactions are referred to as the Krebs, or TCA, cycle. The NADH and $FADH_2$ created in the Krebs cycle then drive the reactions of the electron transport chain, by which hydrogen ions are transported within the mitochondrion, creating a hydrogen ion gradient. This gradient drives chemiosmosis, the final step in this process. At this point, the energy harvested from the original glucose molecule is finally converted into about 38 ATP molecules.



1. Glycolysis. Oxidation of one glucose molecule to form two pyruvic acid molecules yields 2 ATPs and 2 NADH. These will form 6 ATP molecules during the ETC.
2. Formation of two molecules of acetyl coenzyme A yields another 6 ATPs in the electron transport chain.
3. The Krebs cycle. Oxidation of succinyl CoA to form succinic acid yields 2 ATPs, 2 molecules of $FADH_2$ and 6 molecules of NADH.
4. The 6 NADH produced in the Krebs cycle yields 18 ATPs in the electron transport chain. The similarly produced $FADH_2$ yields 4 ATPs in the electron transport chain.

WILEY PLUS Interactivity

The Atkins diet keyed on lipid metabolism. In 1972, cardiologist Robert Atkins rocked the diet world with his book about a "diet revolution" that emphasized protein and fat and discouraged eating vegetables or carbohydrates. When a revised version of the diet was published in 1992, the book became an instant best seller. Dieters waxed rhapsodic about the quick and persistent weight loss they obtained by cutting down on carbohydrates and preferring protein. However, the quick weight loss experienced in the first week is caused by water loss, and that loss cannot be sustained. Starting in the second week, the rate of weight loss slows drastically, because the only way to lose weight is to expend more energy than we take in, and the Atkins diet is calorie-rich.

As Atkins's diet book sold millions of copies, it attracted a storm of criticism from researchers and organizations

concerned with nutrition and obesity. One concern was safety. With heart disease still the nation's number one killer, did it make sense to promote eating fat, which gathers in the arteries and contributes to atherosclerosis? With the antioxidants in vegetables playing an increasingly evident role in good health, should dieters abandon antioxidant-laden broccoli for high-fat meat? Doctors also pointed to the known side effects of a high-protein, high-fat diet, including kidney failure, high blood cholesterol, osteoporosis, kidney stones, and cancer.

It's hard to know whether the Atkins diet failed under a shower of expert criticism, or through the simple fact that people could not stay with it. At any rate, the Atkins diet blazed bright and fizzled like a comet zooming across the night sky.

However, the death of the Atkins diet did not mark the death of the frenzy over fat. The national obesity epidemic continues, and it's safe to predict that another fad diet cannot be far off. We can only hope that your knowledge of human biology will protect you from being taken in by an unhealthy diet. In health, as in jobs, life partners, and promises in general, the same rule applies: If it sounds too good to be true, it probably is.

Our bodies can also make and store lipids. Just as we can catabolize lipids for energy, we can also synthesize and store them. When we consume more calories than are needed to meet our ATP needs, the body converts excess glucose into lipids called **triglycerides**. These are commonly stored in our fat cells, also called *adipose cells*. We are all familiar with the result—fat deposits. Figure 14.7 shows some samples.

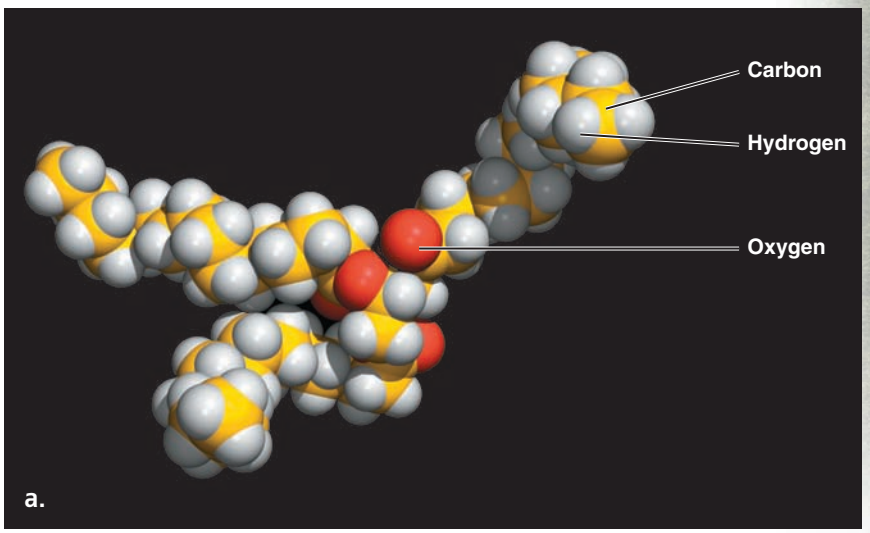
Protein Metabolism Is Also Important to Good Health

Most of the protein we eat is broken down (catabolized) into its component amino acids. Unlike carbohydrates and lipids, proteins are not stored for future use. Instead, the body immediately breaks them apart and uses the released amino acids to create its own proteins. When cells wear out and die, their proteins can also be broken down into amino acids. These amino acids are often recycled to make other proteins. The ribosomes found in almost every cell in our body make proteins out of amino acids, directed by the cell's DNA and RNA. Because proteins are so crucial to everything we do, we need to make sure we get enough from our diet, especially during our growing years, during pregnancy, and at times when we have experienced severe tissue damage.

Once we have enough protein, eating more will not increase our bone or muscle mass. The excess is merely passed from the body. Body mass can be increased only through exercise!

Fat deposits • Figure 14.7

Fat is stored in basically two areas: just beneath the skin (subcutaneously) and deep in body cavities. Some research suggests that females have slightly more subcutaneous fat storage than males, while males have slightly more deep-cavity fat storage.



The caloric value of typical foods and the amount of energy used during moderate exercise • Figure 14.8

Food	Approximate calorie count	Approximate number of minutes of activity required to burn those calories (varies with body weight)
2 slices cheese pizza	800	86–92 minutes of playing basketball
Large blueberry muffin	465	47–57 minutes of mountain climbing
3 chicken wings	360	50–55 minutes of weightlifting
Candy bar	280	45–50 minutes of swimming
Breakfast pastry	170	25–30 minutes of playing Frisbee
Banana	112	30–35 minutes of windsurfing
Serving of strawberry yogurt	108	15–18 minutes of slow jogging
Orange	59	35–37 minutes canoeing

Energy Input Should Match Energy Output

When the amount of energy provided by all the nutrients taken in by the body matches the amount of energy it expends, body weight remains constant. This is known as *energy homeostasis*. When the two amounts don't match, we either gain or lose weight. We know that the amount of energy coming into our bodies is directly related to the food we eat. It is more difficult to calculate energy expenditure. Energy expenditure depends on our basal metabolic rate (the rate at which all our metabolic reactions use energy when we are resting and quiet), the amount of physical activity we engage in, and the heat given off by food being digested and stored.

The amount of energy we expend can fluctuate dramatically. During heavy exercise, we may use 15 times as much energy as we use when at rest. Children tend to expend more energy because of all the reactions in their bodies related to growth, and much older people often expend less energy than they did when they were young.

To maintain energy homeostasis, we need to regulate our energy intake and expenditure. **Figure 14.8** indicates the caloric value of some common foods, along with the amount of exercise needed to use that energy. In the next section we discuss what happens when we don't regulate our energy intake and output.

CONCEPT CHECK

1. **Where** does each step in carbohydrate metabolism occur?
2. **Why** is protein metabolism more difficult for the body than lipid or carbohydrate metabolism?
3. **What** are the factors that determine how much energy our bodies expend?

14.3 Health Can Be Hurt by Nutritional Disorders

LEARNING OBJECTIVES

1. **Determine** how to calculate a healthy weight for your personal lifestyle and body size.
2. **List** and define the most common type of food poisoning.
3. **Describe** the world health issues surrounding nutrition.

Diet and nutrition are important aspects of overall health because most of the compounds that enter the body do so via the digestive system. If we put nothing useful into the digestive system, our bodies will not have a good source of raw material for the proteins, enzymes, and energy required for life. Conversely, if we fill the digestive system with foods that are high in necessary nutrients, our bodies will function at peak levels. Of course, we can get too much of a good thing. If we ingest more calories than we "spend," regardless of their quality, we will store the excess in adipose tissue as fat (triglycerides).

Much attention is given to our diet and its effect on the body, both in the media and in society at large. Our society is obsessed with being thin. For some, this obsession leads to one of two common eating disorders, **anorexia nervosa** and **bulimia nervosa**. Both disorders stem from the desire to be thin and, therefore, "beautiful." Eating disorders grow out of a culture that is obsessed with beauty, and it will be difficult to reduce their prevalence without changing societal attitudes about beauty. Hopefully, as we become more aware of health and nutritional issues, we will recognize the beauty of a healthy, well-proportioned body rather than a tall, rail-thin one. Interestingly, in other cultures of the world, being rail-thin is not at all desirable. Instead, that level of thinness indicates an inability to obtain proper nutrition, which is understandably not considered beautiful.

The opposite nutritional disorder is **obesity**. Some health professionals worry that obesity is becoming widespread. See *Ethics and Issues: How Far Should You Go to Look Skinny?* Obesity is usually defined in terms of **body mass index (BMI)**. You can calculate your BMI by dividing your weight in kilograms by the square of your height in meters. You can also consult a BMI chart like the one in Figure 14.9. Your BMI should give you an indication of how much of your weight is due to fat stored in adipose tissue. BMIs over 32 are generally considered to indicate obesity. However, if you are muscular or have denser or lighter bones than average, your BMI may not be an accurate indication of obesity.

BMI is a rough estimate of the amount of body fat present. To use this table, you find your height along the left column and your weight along the top row. Where these two meet is your BMI. A BMI between 18.5 and 24.9 is considered "normal and healthy," while those with BMI below 18.5 are labeled underweight and those above 30 are considered obese.

The body mass index • Figure 14.9

Weight in Pounds

Height in Feet and Inches	120	130	140	150	160	170	180	190	200	210	220	230	240	250
4′6″	29	31	34	36	39	41	43	46	48	51	53	56	58	60
4′8″	27	29	31	34	36	38	40	43	45	47	49	52	54	56
4′10″	25	27	29	31	34	36	38	40	42	44	46	48	50	52
5′0″	23	25	27	29	31	33	35	37	39	41	43	45	47	49
5′2″	22	24	26	27	29	31	33	35	37	38	40	42	44	46
5′4″	21	22	24	26	28	29	31	33	34	36	38	40	41	43
5′6″	19	21	23	24	26	27	29	31	32	34	36	37	39	40
5′8″	18	20	21	23	24	26	27	29	30	32	34	35	37	38
5′10″	17	19	20	22	23	24	26	27	29	30	32	33	35	36
6′0″	16	18	19	20	22	23	24	26	27	28	30	31	33	34
6′2″	15	17	18	19	21	22	23	24	26	27	28	30	31	32
6′4″	15	16	17	18	20	21	22	23	24	26	27	28	29	30
6′6″	14	15	16	17	19	20	21	22	23	24	25	27	28	29
6′8″	13	14	15	17	18	19	20	21	22	23	24	25	26	28

Underweight | Healthy weight | Overweight | Obese

WILEY PLUS Video

ETHICS AND ISSUES

How Far Should You Go to Look Skinny?

Obesity is quickly surpassing smoking as the number one preventable cause of death in the United States. Americans are literally killing themselves with their food choices—and they are not alone in this self-inflicted epidemic. World Health Organization reports that in 2008 there were over 1 billion overweight adults in the world, with a full 300 million of them classified as clinically obese. Although initially thought to be a problem of industrialized societies, the rate of obesity in developing countries is rising at an even faster rate.

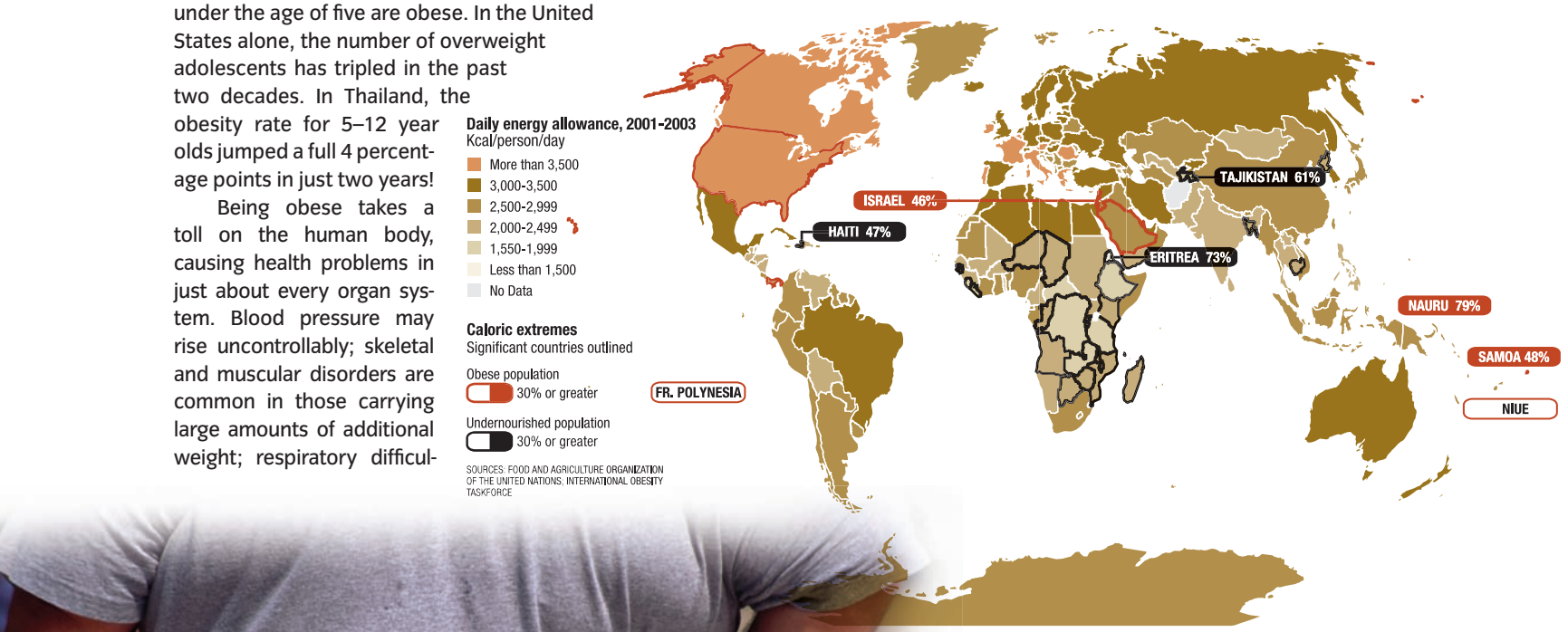
Using body mass index (BMI) as a measure of obesity provides a good comparison for various countries. A BMI below 18.5 kg/m^2 is considered underweight, while a BMI of 25–29 kg/m^2 is considered overweight. A BMI over 30 kg/m^2 is obese. Adult BMI's range from 22–23 kg/m^2 in Africa and Asia, and to 25–27 kg/m^2 across North America, Europe, Latin America, North Africa, and most Pacific Island countries. Obesity rates range from below 5% in the developed areas of China, Japan, and some African nations to over 75% in relatively less developed urban Samoa.

Perhaps even more distressing than the worldwide explosion of obese adults is the increase in childhood obesity. WHO estimates that worldwide, over 22 million children under the age of five are obese. In the United States alone, the number of overweight adolescents has tripled in the past two decades. In Thailand, the obesity rate for 5–12 year olds jumped a full 4 percentage points in just two years!

Being obese takes a toll on the human body, causing health problems in just about every organ system. Blood pressure may rise uncontrollably; skeletal and muscular disorders are common in those carrying large amounts of additional weight; respiratory difficulties can develop as the upper respiratory system carries more tissue; cardiovascular disease rates rise as weight increases; the risks of developing gallbladder disease or cancer rise with increasing weight; and the incidence of type 2 diabetes rises dramatically with excessive weight gain. All of these health concerns increase the cost of health care in developed nations.

Critical Reasoning Issues Recently in the United States, the television show *Dance Your *#@ Off* has become popular. During this reality show, obese contestants are brought together, taught proper nutrition and diet choices, given workout regimes, and taught to dance. They compete against one another in both dancing and weight loss. Those that score the highest marks on their dance and also lose the largest percentage of their body weight each week get to stay on the show, learning and losing even more.

NATIONAL GEOGRAPHIC



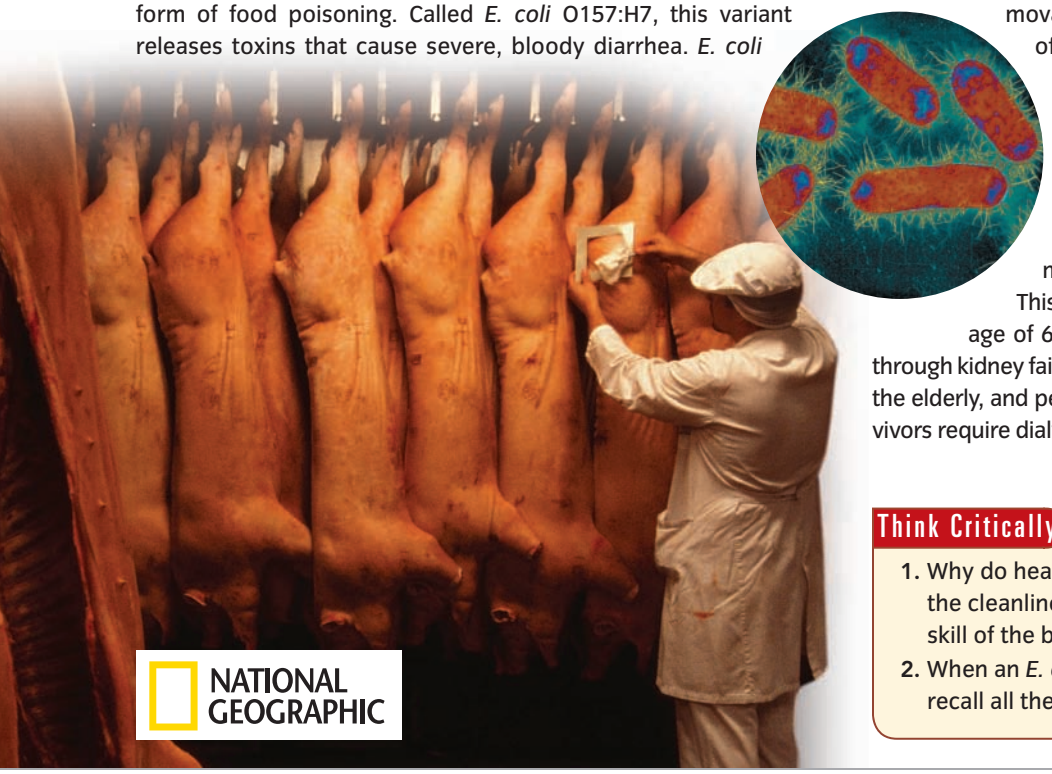
Think Critically

1. What might be the emotional draw for this sort of reality TV? Can the lessons taught to these contestants be expected to spread through the viewing public? Is this a good way to teach healthy living without alienating anyone?
2. Some people feel that being overweight is not a problem, but rather a genetic predisposition or a lifestyle choice. Are overweight individuals right to defend their size? Is obesity a societal matter, or an individual choice?

WHAT A SCIENTIST SEES

A Hidden Peril: *E. Coli*-Infested Food

Bacteria are divided into "strains" based on specific genetic traits, and one of the many strains of *E. coli* causes a severe form of food poisoning. Called *E. coli* O157:H7, this variant releases toxins that cause severe, bloody diarrhea. *E. coli* contamination usually occurs in the slaughterhouse, when an animal's large intestine is inadvertently opened during removal. The contents may spill onto the edible cuts of meat, contaminating them. The Centers for Disease Control and Prevention (CDC) estimate that *E. coli* O157:H7 causes about 73,000 illnesses per year. Most infections clear up after 5 to 10 days. Antibiotics are not needed and, if used, may contribute to kidney damage.



In rare cases, *E. coli* O157:H7 can cause a far more serious disease, *hemolytic uremic syndrome*. This disease kills red blood cells and causes an average of 61 fatalities each year in the United States, mainly through kidney failure. The syndrome is most severe among children, the elderly, and people with immune system deficiencies. Some survivors require dialysis; others can suffer blindness or paralysis.

Think Critically

1. Why do health inspectors routinely observe and evaluate the cleanliness of slaughterhouses and the professional skill of the butchers?
2. When an *E. coli* outbreak is suspected, why does the FDA recall all the meat from that particular packing house?

Food Is Life Sustaining, but Sometimes It Can Be Life Threatening

Eating disorders are not the only pathologies involving nutrition and food. There are almost as many food-borne diseases as there are foods to carry them. More than 250 **food-borne diseases** are known, ranging from bacteria and viruses to parasites and toxins contained in the foods themselves. The many types of food poisoning share a common thread: The causative pathogens are usually found growing in or on the foods we eat. These pathogens enter the body through the digestive tract. Symptoms vary, but the immediate symptoms usually include nausea, vomiting, abdominal cramps, and/or diarrhea. The symptoms represent the body's attempt to rid itself of the pathogen or toxin. If these flushing techniques fail, we will experience the specific symptoms of the invading organism.

There are three common types of bacteria that can cause food poisoning. The three most common types of bacteria that can cause food poisoning are *Campylobacter, Salmonella*, and *Escherichia coli (E. coli)*.

Campylobacter is a normal resident of the intestinal tract of chickens and other fowl. Commonly ingested in undercooked poultry, *campylobacter* is the primary cause of bacterial diarrhea.

Salmonella, found in the intestines of birds, reptiles, and mammals, causes the usual food poisoning symptoms but can become much more serious if untreated. Salmonella can escape from the intestinal tract and enter the bloodstream, leading to **septicemia**, a life-threatening condition in which the blood carries a poison throughout the body.

E. coli is normally present in the colon of cattle, pigs, and humans. The healthy human colon is a sea of bacteria, including vast numbers of *Escherichia coli (E. coli)*. In-

side the gastrointestinal tract, almost all *E. coli* are helpful or at worst harmless. We often hear about outbreaks of *E. coli* infections that cause serious illness for a few unfortunate victims, or outbreaks that sweep entire small towns. Recently, 146 U.S. citizens in 23 states suffered from *E. coli* poisoning, and one person died. All of these cases have been traced to tainted spinach crops, causing a crisis in the spinach and lettuce industry.

E. coli normally live in the intestines of healthy cattle and some other ruminants. Many human infections come from meat that has been contaminated by the contents of cattle intestines at the slaughterhouse. Ground beef is a common carrier because the bacteria can reside deep inside the meat, where it cannot be washed off or easily heat-sterilized by cooking. The tainted spinach was a result of watering with reclaimed water that had not been properly sterilized before being sprayed onto the crops. (Find out more about *E. coli* in *What a Scientist Sees*.)

Viruses can also contaminate food. The most common viral food contaminant is calicivirus, or Norwalk-like virus, which causes vomiting that lasts for approximately two days, with little diarrhea or fever. Norwalk-like virus has spread through the general population from fishers who have become infected through their oyster catch. Stomach flu has similar symptoms; it is actually not influenza but, rather, a viral infection that attacks and irritates the stomach and small intestine. Stomach flu is transmitted through kissing, touching, or sharing food, drinks, or utensils. Food preparation workers who carry the virus can spread it through the food they handle.

Maintaining fluid homeostasis is a matter of survival. Whether the body's homeostatic balance is disrupted by food-borne illness or merely by eating, we must have a system in place to restore it. These changes must be rectified to keep the blood and other body fluids at specific levels. Maintaining fluid homeostasis is a matter of survival. Monitoring and maintaining the composition of the blood and the entire internal environment is the job of yet another system, the urinary system, which is covered in Chapter 16. Occasionally, the foods we eat include environmental toxins and contaminants, which in turn cause us more problems as our urinary system works to remove these toxins. For a look at how these contaminants get into our food supply, see *Health, Wellness, and Disease: How Do Environmental Agents Become Concentrated in My Food?*

Food Shortages Cause Other Nutrition-Related Problems

Severe food shortages exist in many parts of the world. These shortages occur primarily in developing countries as environmental, economic, and social hardships often force people to abandon their homes and their livelihoods. It is often difficult to import food for these migrating masses because of obstacles created by warfare, drought, or other natural disasters. The resulting mass starvation and malnutrition put serious strains on already impoverished countries.

Malnutrition literally means "bad nutrients" and is a condition caused by an inadequate diet. The diet can be lacking in calories or low in specific vitamins and minerals. Malnutrition can also be due to infections that cause vomiting or diarrhea, which result in the loss of previously ingested nutrients. In developing countries, malnutrition accounts for many deaths, especially of infants and the elderly, and can produce substantially lower intelligence in those who survive.

Protein energy malnutrition (PEM) and micronutrient malnutrition are common forms of this global problem. A distended belly, as seen in **Figure 14.10**, is indicative of

A child suffering from kwashiorkor • Figure 14.10

Kwashiorkor is common in Africa, Central and South America, and southern Asia. It usually appears in weaned children, as mother's milk contains enough amino acids to prevent it from occurring in nursing infants. Because the early-childhood diet in these impoverished areas is lacking in meat and milk products, children are vulnerable to protein deficiency.

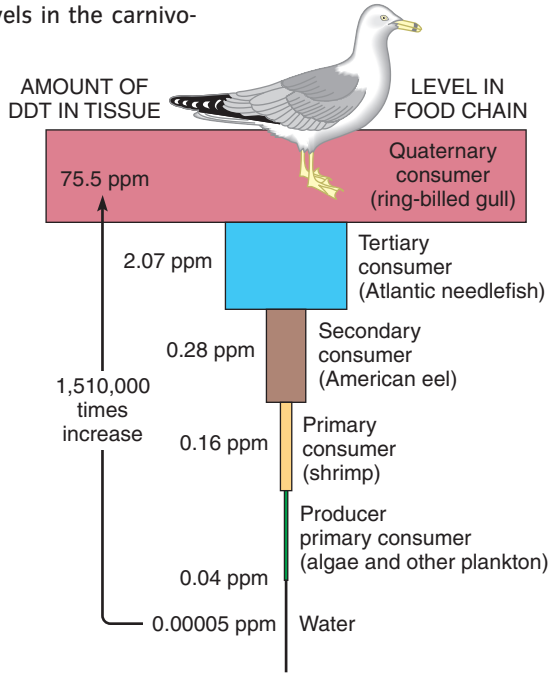
HEALTH, WELLNESS, AND DISEASE

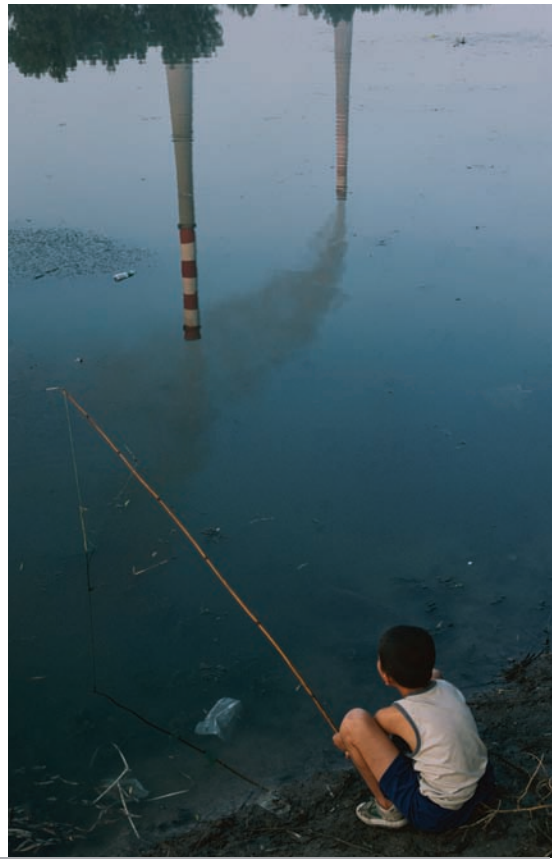
How Do Environmental Agents Become Concentrated in My Food?

NATIONAL GEOGRAPHIC

If we are what we eat, our environment is literally a part of us. Our food is a product of the environment, and when that food absorbs potentially toxic pollutants, some of those pollutants become a part of us as well. The term *biomagnification* refers to the concentration of toxins (compounds and elements that disrupt physiology, leading to cellular death) as they move up the food chain. If heavy metals released into surface waters by a manufacturing plant are absorbed by plankton, and the plankton is eaten by small fish, which are eaten by bigger fish, which are then eaten by us, the toxins will become more concentrated at each step along the way—increasing from nonhazardous levels in the plankton to hazardous levels in the carnivorous fish.

A dramatic example of this process occurred in Minamata, Japan, where, after eating fish containing high levels of mercury in the 1960s, upward of 2,200 people died or were disabled. The methyl mercury had been discharged by a manufacturing plant and had become increasingly concentrated as larger fish ate smaller fish and were in turn eaten by the residents of Minamata. Several areas in the United States, and especially the Great Lakes region, are monitored for evidence of biomagnification that could affect human food. It is worth noting that most elements do not biomagnify; persistent organic pollutants (POPs) do, however, because they tend to break down slowly and are fat-soluble. The organic forms of mercury, cyanide, chromium, and polychlorinated biphenyls (PCBs) are POPs.





kwashiorkor, a series of complications resulting from protein deficiency in children. These children are taking in enough calories but are lacking in essential amino acids. Often, simply restoring a healthy diet can alleviate the symptoms of malnutrition. If a child has passed certain developmental stages, however, permanent damage may result from either micronutrient malnutrition or PEM.

CONCEPT CHECK

STOP

1. **What** factors are involved in calculating your body mass index? **How** do you determine if your BMI indicates a healthy body weight?
2. **How** are *Campylobacter*, *Salmonella*, and *E. coli* related? **Where** are they usually found? **What** do they usually cause if ingested?
3. **What** are the world health issues surrounding nutrition?

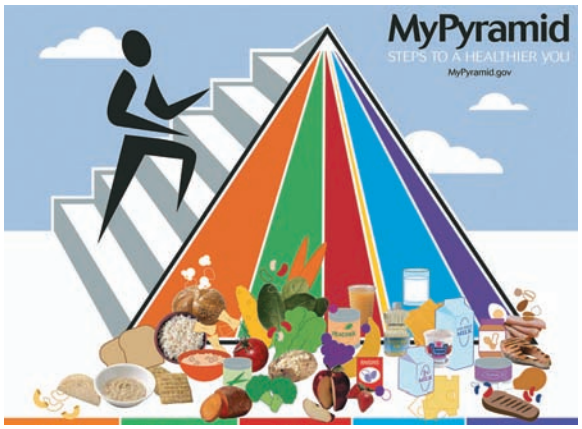
Summary

THE PLANNER

1 Nutrients Are Life Sustaining 378

- Food contains macronutrients—carbohydrates, fats, and proteins—and micronutrients—vitamins and minerals. Vitamins are organic substances; minerals are inorganic. Both are necessary for maintaining homeostasis. Although vitamins and minerals can be obtained safely from over-the-counter supplements, a healthy diet is rich in fruits and vegetables, which provide these **nutrients** naturally.
- How much and what type of food we ingest plays a large role in our health. The U.S. Food and Drug Administration has recently upgraded the basic food pyramid (shown here) to factor in age, activity levels, and gender.

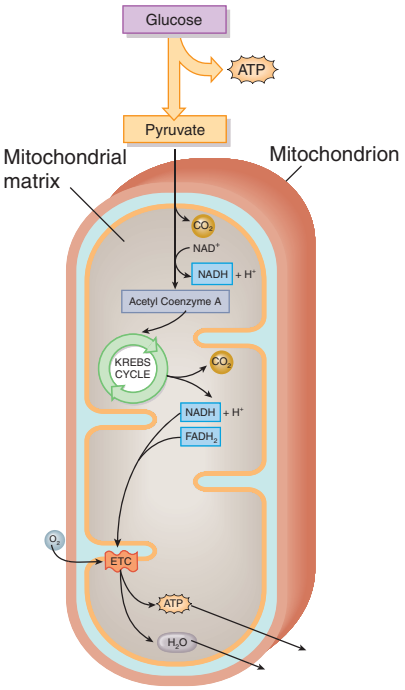
Figure 14.5



2 Nutrients Are Metabolized 390

- **Metabolism** refers to the chemical reactions in the body that break down nutrients and build compounds. These reactions may be either anabolic or catabolic. Anabolic reactions build larger molecules and consume energy, whereas catabolic reactions break down molecules and release energy. Carbohydrates, lipids, and proteins all undergo both anabolic and catabolic reactions, as shown in the diagram.

Figure 14.6



- When the amount of energy provided by all the nutrients we consume matches the amount of energy used by our bodies, our weight remains constant. We have achieved energy homeostasis. When the two don't match, we either gain or lose weight.

3 Health Can Be Hurt by Nutritional Disorders 394

- The primary nutritional disease in the United States is obesity. The major eating disorders are anorexia nervosa and bulimia nervosa. All can be treated with a combination of proper diet and professional mental health care.
- A number of food-borne pathogens, both bacterial and viral, can cause disease, but good sanitation can prevent many of them from spreading.
- Food shortages in many parts of the world also create health concerns. Malnutrition affects entire countries, causing underdeveloped intellect and, in the worst cases, death of the very young and the very old. As shown in this photo, kwashiorkor is a common health problem for children in developing countries.

Figure 14.10

Key Terms

- aerobic 378
- calorie 382
- chemiosmosis 390
- glycolysis 390
- metabolism 390
- milled 389
- nutrients 378
- vegan 383

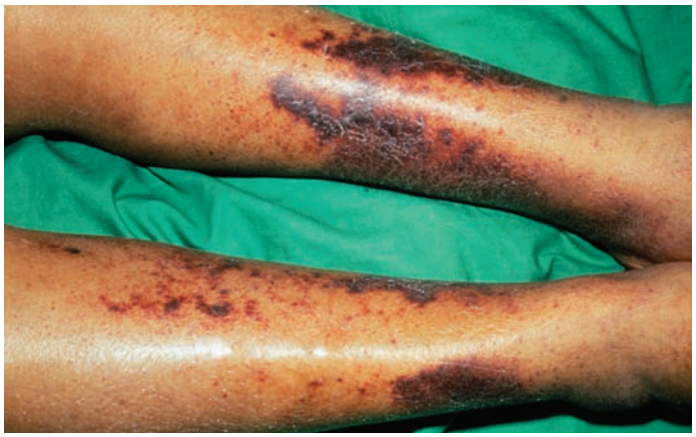
Critical and Creative Thinking Questions

1. Go to the MyPyramid Web site (http://www.mypyramid.gov) and obtain your personal food guide. Then alter your personal characteristics and compare the results. Describe what happens to the recommended guidelines as you age. What happens if your exercise level increases? Are these changes the same for males and females, or does gender alter the caloric recommendation?
2. Recently, the media have promoted the idea of consuming only locally grown, organic produce. Are there any nutritional values that might be present in locally grown produce that might not be present in produce shipped in from other areas of the country? What other benefits might "eating local" have for an individual? For a community? How does organic farming differ from traditional farming?
3. What can you do to avoid food poisoning? Do you take any precautions when preparing food? Outline a sensible plan for maintaining food safety in your kitchen.
4. CLINICAL CLICK QUESTION
   Sarah thought she was doing well despite her poverty-level subsistence, eating bread and peanut butter and the occasional vegetable when she could afford it. Her protein intake was low, but sufficient due to the peanut butter, and she was careful to get a little fat in her diet when she could. Therefore when she developed symptoms of malnutrition, Sarah was startled. Her symptoms included cracking and bleeding lips and nostrils, an aggravation and re-appearance of old scars, and an odd-looking rash on her skin. Upon further investigation, she saw that the rash she had developed was due to bleeding just under the skin as capillaries were breaking down. As time went on without a change in her diet, Sarah noticed that her gums felt "soft" and her teeth started to loosen.

   What type of tissue seems to be most affected by Sarah's dietary imbalance? What class of nutrient might Sarah be lacking in her diet?

   Finally going to the doctor, she was surprised to hear that she had a vitamin deficiency. A piece of fruit or even a potato daily was all it took to correct this deficiency.

   Lack of which vitamin caused Sarah's symptoms? Check Table 14.3 for assistance in your diagnosis. This disease was referred to as the "scourge of the seas" during the 17th century, and is on the rise again in England. See http://www.dailymail.co.uk/health/article-1225905/Seafarers-disease-Scurvy-rise-children-lack-vitamin-C-diet.html for more information on this latest outbreak.



What is happening in this picture?

NATIONAL GEOGRAPHIC

The "freshman 15" is a common phrase referring to the typical 15-pound weight gain that most students experience in their first year away from their family's home-cooked meals. Often, students are gathered around a pizza and a few beers, arguably the most commonly consumed meal on college campuses. Is this a bad choice, assuming that all the students are over age 21?

Think Critically

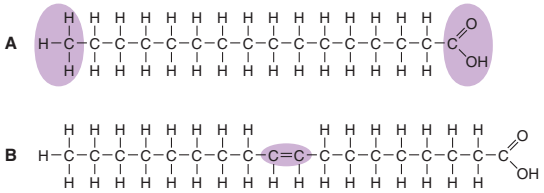
1. What food groups are present in a meal consisting of an "everything" pizza, a beer, and a glass of water?
2. Are those food groups present in the appropriate relative quantities, or are some in higher concentration than is recommended for energy homeostasis?
3. Does this meal provide adequate micronutrients?
4. How might this type of meal add to the "freshman 15"?

Self-Test

1. Macronutrients include all of the following EXCEPT _____.
   a. carbohydrates
   b. lipids
   c. vitamins
   d. proteins

2. Our best source of energy is _____.
   a. vitamins
   b. carbohydrates
   c. lipids
   d. amino acids

3. In the figure below, is the molecule of unsaturated fat indicated?
   a. It is indicated as A.
   b. It is indicated as B.
   c. Neither of these molecules is an unsaturated fat.
   d. Both of these molecules are unsaturated fats.



4. LDL is a lipid containing _____ protein and _____ cholesterol than HDL.
   a. less/more
   b. more/less
   c. less/less
   d. more/more

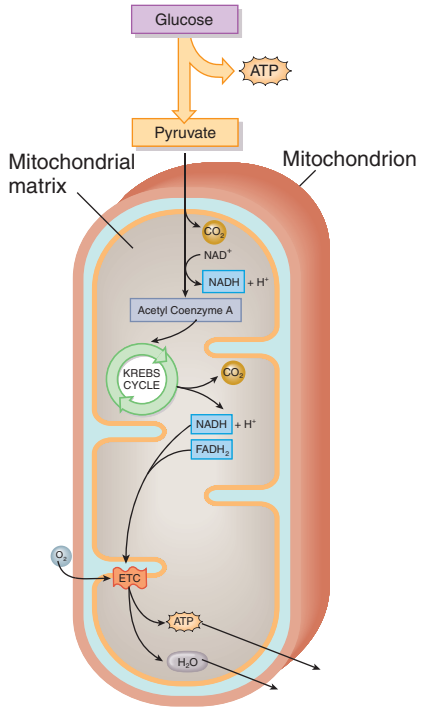
5. Complete proteins _____.
   a. include all essential and nonessential amino acids.
   b. are found in animal flesh.
   c. can be obtained from certain vegetables.
   d. All of the above are correct.

6. The MyPyramid Web site is designed to give you _____.
   a. information from which to determine your BMI
   b. easy access to information about the caloric content of most common foods
   c. tips on healthy eating based on your gender, age, and activity level
   d. assistance in reducing obesity

7. Calcium, zinc, and iodine are all examples of vitamins.
   a. True
   b. False

8. Fat-soluble vitamins include vitamins _____.
   a. A, D, and B
   b. B and C
   c. A, D, and E
   d. All vitamins are fat-soluble.

Questions 9 and 10 relate to this diagram.



9. The reactions in this diagram are collectively referred to as _____.
   a. chemiosmosis
   b. the Krebs cycle
   c. mitochondrial reactions
   d. cellular respiration

10. The first step in the reaction shown _____.
    a. is called glycolysis
    b. converts one glucose molecule into two pyruvate molecules
    c. releases a net of two ATP molecules
    d. All of the above describe the first reaction shown.

11. The eating disorder anorexia nervosa can be described as _____.
    a. severe undereating
    b. food poisoning
    c. overeating
    d. the binge–purge disease

12. The bacterium *E. coli* is normally found _____ of mammals.
    a. in the colon
    b. in the small intestine
    c. in the stomach
    d. throughout the digestive system

13. Maintaining a healthy weight requires _____.
    a. monitoring caloric intake
    b. regulating energy output
    c. increasing metabolic rate with age
    d. Both a and b are correct.

14. The type of food poisoning that is usually spread through poorly prepared chicken is _____.
    a. *E. coli*
    b. *Salmonella*
    c. *Campylobacter*
    d. *stomach flu*

15. Biomagnification can be a problem _____.
    a. in children immediately after weaning when dietary proteins are in short supply
    b. in areas where malnutrition is evident
    c. when eating top-level predators from a polluted environment
    d. when preparing food without proper sanitation

THE PLANNER

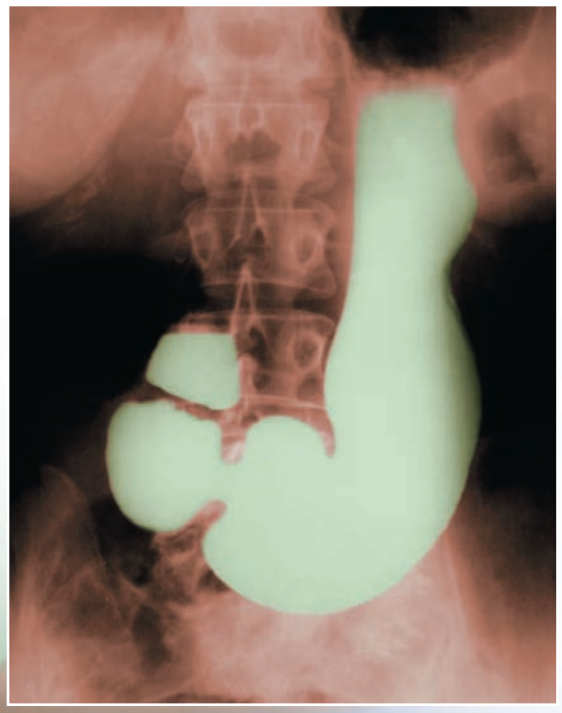
Review your Chapter Planner on the chapter opener and check off your completed work.

The Digestive System

Many of us have seen some version of an eating contest, the most famous of which takes place every Fourth of July on Coney Island in New York. Nathan's Famous Fourth of July International Hot Dog Eating Contest began in 1916, and the winner gets the Mustard Belt, notoriety, and a dose of indigestion (or worse). Recent winners have consumed more than 60 hot dogs and buns in 12 minutes—that's nearly 20,000 calories and countless grams of fat in one sitting!

The strains put on the digestive system during such contests are explored in a National Geographic special called "The Science of Speed Eating," which follows a competitive eater who has trained his body to ignore the signals of fullness and to stretch his stomach to incredible proportions. Competitive eating is not for the weak. It has real dangers, including stomach perforations, esophageal tears, and an overwhelmed digestive system. There is also considerable question as to whether eating 44 lobsters or 552 Louisiana oysters in 10 minutes (done by speed eater Sonya Thomas, known as the "Black Widow") is an enjoyable experience.

Our digestive system is both simple and complicated. It is a series of closely related organs designed to extract from the food we eat every last gram of the nutrients studied in Chapter 14. In this task, the digestive organs are almost too good at what they do, but if and when they are abused or diseased, they can make our lives miserable.



CHAPTER OUTLINE

Digestion Begins in the Oral Cavity 404

- The GI Tract Remains the Same Throughout Its Length
- The Mouth Starts It All
- The Esophagus Connects the Oral Cavity with the Stomach

The Stomach Puts Food to the Acid Test 410

- The GI Tract Has Major Modifications at the Stomach
- Gastric Digestion Includes Three Phases

The Intestines and Accessory Organs Finish the Job 413

- The Small Intestine Completes the Nutrition Extraction Phase
- Accessory Organs Help Finish the Job
- The Large Intestine Absorbs and Reabsorbs

Digestion Is Both Mechanical and Chemical 422

- Unlike Mechanical Digestion, Chemical Digestion Alters Chemical Bonds
- The Digestive System's Job Is to Prepare Nutrients
- Regulation of Our Digestive Activities Is Based on Blood Sugar Levels

CHAPTER PLANNER

- ❑ Study the picture and read the opening story.
- ❑ Scan the Learning Objectives in each section:
  p. 404 ❑ p. 410 ❑ p. 413 ❑ p. 422 ❑
- ❑ Read the text and study all figures and visuals. Answer any questions.

Analyze key features

- ❑ What a Scientist Sees, p. 408
- ❑ I Wonder..., p. 411
- ❑ Process Diagram, p. 412
- ❑ Biological InSight, p. 414
- ❑ Health, Wellness, and Disease, p. 419
- ❑ Ethics and Issues, p. 425
- ❑ Stop: Answer the Concept Checks before you go on:
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End of chapter

- ❑ Review the Summary and Key Terms.
- ❑ Answer the Critical and Creative Thinking Questions.
- ❑ Answer What is happening in this picture?
- ❑ Answer the Self-Test Questions.

15.1 Digestion Begins in the Oral Cavity

LEARNING OBJECTIVES

1. **Explain** the processes and functions of the digestive system.
2. **Describe** the general anatomy of the digestive tract.
3. **List** the digestive organs in order from mouth to anus.
4. **Discuss** the structure and function of the esophagus.

The digestive system is sometimes called a "tube within a tube," because it is basically a hollow structure with two openings that runs the length of your body. The digestive system has two major parts, the "gastrointestinal system," or **GI tract**, and a set of **accessory organs**. The GI tract begins at the oral cavity, winds through the abdominal cavity, and ends at the anus. The major accessory organs include the pancreas, the liver, and the gallbladder. Together, the GI tract and the accessory organs carry out five basic processes:

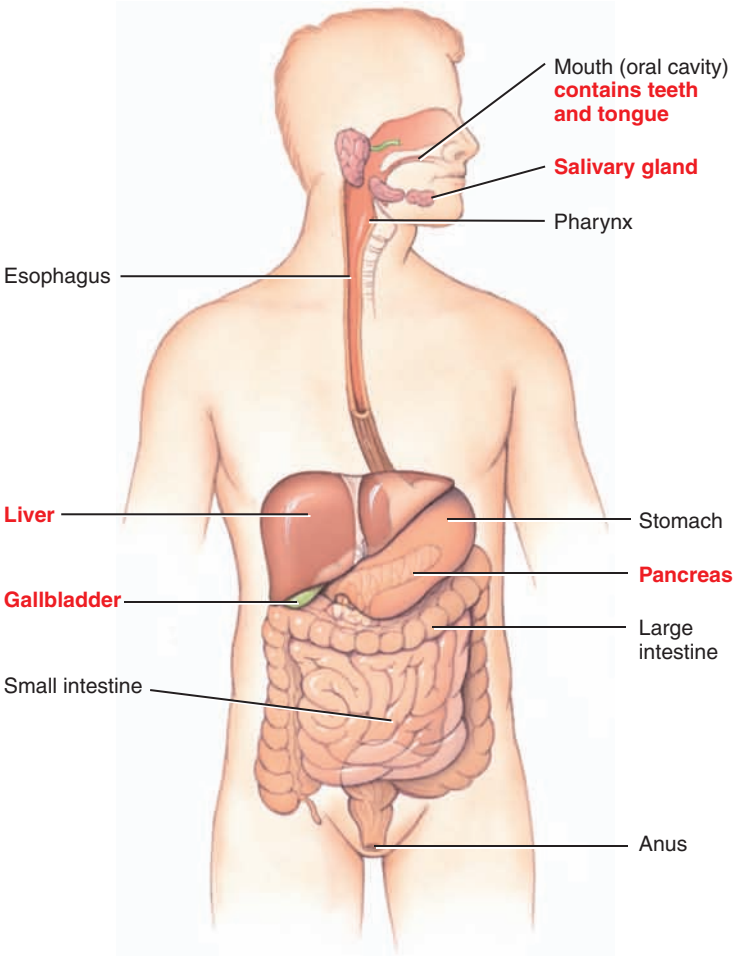
1. **Ingestion**. Foods and liquids are taken into the mouth and eaten.
2. **Mixing**. The smooth muscle in the walls of the GI tract mixes the food and sends it on its way through the tract.
3. **Digestion**. Food is broken down by both mechanical and chemical processes.
4. **Absorption**. The epithelial cells lining the GI tract absorb the digested food molecules and pass them to the blood or lymph.
5. **Defecation**. Any substance not digested or absorbed, for whatever reason, is passed along to the end of the GI tract, the anus, and leaves the body.

Figure 15.1 shows an overview of the digestive system.

The GI Tract Remains the Same Throughout Its Length

The structure of the GI tract is essentially the same along its entire length. It is composed of four layers:

- The innermost layer is composed of a mucous membrane, or **mucosa**. This slippery, smooth layer allows ingested food to move along the tract without tearing it.
- Under the mucosa, the **submucosa** includes the glands, nerves, and blood supply for the tract itself.



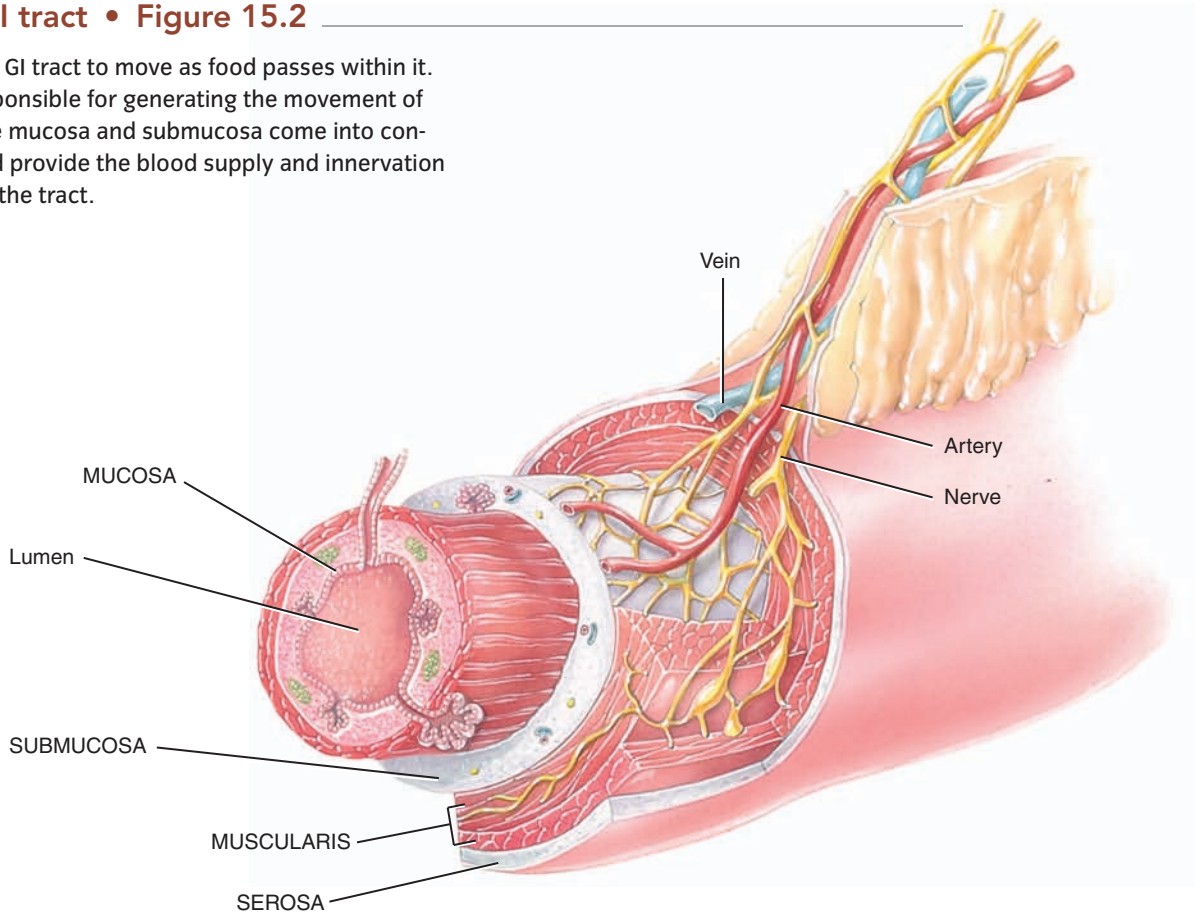
Right lateral view of head and neck and anterior view of trunk

Digestive system overview • Figure 15.1

The tubular structure of the GI tract is obvious when looking at it in its entirety. The tube begins at the esophagus and, with slight modifications, travels the length of the tract, ending at the anus. These modifications alter the function of the tract at various points, which we describe as different organs. Accessory organs aid in digestion, and are found along the length of the GI tract. Accessory organs are named in red above.

Layers of the GI tract • Figure 15.2

The serosa allows the GI tract to move as food passes within it. The muscularis is responsible for generating the movement of the tube, whereas the mucosa and submucosa come into contact with the food and provide the blood supply and innervation for the inner lining of the tract.



- The **muscularis** gives the tract the ability to move substances lengthwise. For most of the tract, the muscularis is composed of one layer of longitudinal muscle above another layer of circular muscle.
- The outer layer of the GI tract, the **serosa**, is a slippery membrane that permits the tract to move inside the abdominal cavity without catching or causing discomfort. Your digestive system is always active, as muscular contractions shift, lengthen, and shorten the tube. Although this movement is constant, you normally neither see nor feel it.

peristaltic wave
Rhythmic muscular contractions of a tube that force contents toward the open end.

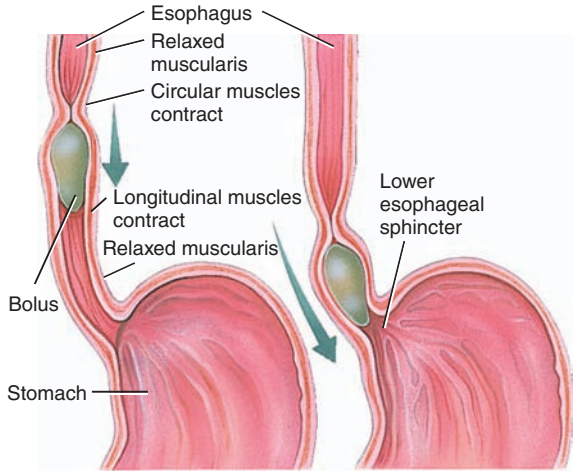
These layers (Figure 15.2) work in unison to create the **peristaltic wave** that propels food through the tube, as seen in Figure 15.3.

The Mouth Starts It All

The best way to understand the actions of the digestive system is to follow some food through the GI tract, starting at the oral cavity, or mouth. Think about a hot slice

Peristaltic wave generation • Figure 15.3

The peristaltic wave is generated as you consciously swallow food. Movement of the tongue initiates the muscularis to begin a ring of contraction that is passed throughout the entire tract. Once you swallow food, the peristaltic wave travels the length of the tube; you no longer have conscious control over those smooth muscle contractions.



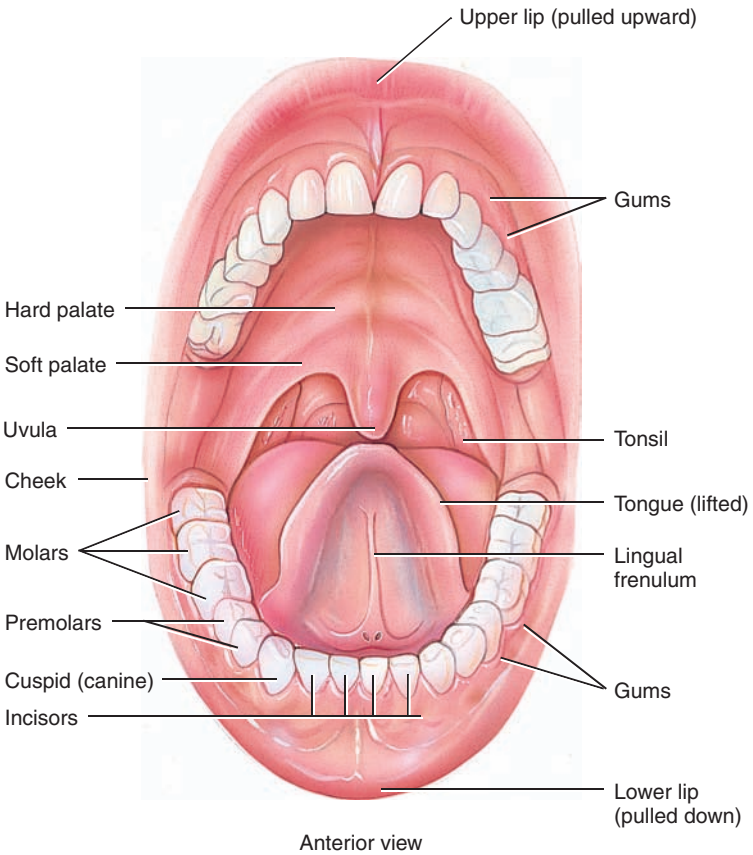
Anterior view of frontal sections of peristalsis in esophagus

of pizza. How does it provide energy and nutrients? Let's follow that slice along the digestive tract, and see how the body pulls nutrients from it and how its energy is used to create ATP for immediate use or adipose tissue for energy storage.

The pizza enters the digestive tract through the oral cavity. We tear off a bite of pizza with **incisors** and then crush it with the **molars** and **premolars**. Teeth and accessory organs then function as cutting tools (incisors), piercing and ripping utensils (canines), or grinding instruments (molars and premolars). Although we are not born with teeth extending through the gums, they erupt soon after birth in a predictable pattern. Incisors appear first, allowing food to be bitten off, often by 8 months of age. The premolars and molars appear last, with "wisdom teeth," our final set of grinding molars, appearing sometimes as late as our mid-twenties or early thirties.

Oral cavity • Figure 15.4

The teeth and tongue in the oral cavity are ideal for mechanical digestion. The food is rolled around with the tongue and broken into smaller pieces with the teeth.



Anterior view

We first obtain 20 primary, deciduous, or baby teeth. These are replaced by our 32 permanent teeth, usually by age 21 (**Figure 15.4**).

The small bits of pizza are **macerated** with saliva. **Mechanical digestion** increases the efficiency of enzymes in the stomach and small intestine by creating small bits of food, still chemically identical to the original bite of pizza, with a great deal of surface area where enzymes can carry out the process of **chemical digestion**.

macerated Soaked until soft and separated into constituent parts.

mechanical digestion The physical crushing, chopping, and cutting of food.

chemical digestion The breaking down of food using enzymes that alter the chemical structure of the food.

Most people try to take good care of their teeth, with regular brushing, flossing, and visits to the dentist. Why do we bother with such dental cleanliness? Our mouths contain hundreds of species of bacteria, which live on the oral surfaces and multiply rapidly when sugar is available. These bacteria excrete wastes as they grow and metabolize. The wastes are usually acidic, and if the acid remains on tooth surfaces, it can eat through the enamel to the softer **dentin** at the center of the tooth. **Plaque** is a combination of the bacterial colonies, their bacterial wastes, leftover sugars from chewed up food, epithelial cells from the host, and saliva. Plaque begins as a sticky substance on the surfaces of the teeth but can calcify with time into the tough layer of tartar your hygienist must scrape off.

The largest increase in bacterial growth occurs 20 minutes after eating. The bacterial colonies are metabolizing the food from your last meal, growing and dividing at their highest rate roughly 20 minutes after you eat. As the bacteria are multiplying rapidly, they are digesting the sugar in your mouth and creating large quantities of acidic waste. Once the food is removed, the bacterial division slows. If you do not thoroughly and routinely remove this buildup of bacteria and acid, the acid may decay the enamel on the teeth, causing cavities. A cavity does not cause pain at first, but as the acids reach farther into the tooth, they eventually hit softer tissue near the tooth's nerve, called the **pulp**. By this time, the cavity is quite large and will require dental repair.

The recommended biannual dental cleaning is a great way to monitor plaque buildup and cavity formation. While removing plaque, the hygienist may spot any small cavities, which the dentist can repair before they destroy the pulp of the tooth. The repair process involves drilling out all rotten material and replacing it with an airtight seal made of gold, silver alloy, or composite resin.

The tongue balls things up. The tongue, another accessory organ, manipulates the now-crushed pizza into a **bolus** and positions that bolus at the back of the oral cavity so it can be swallowed. The tongue is a muscle that can move in almost any direction in the oral cavity. On its surface, keratinized epithelium covers each **papilla**, creating a rough texture to help move the slippery food into position where the teeth can masticate it. Taste buds reside along the sides of the papillae. The tongue also secretes watery mucus containing a digestive enzyme, **lingual lipase**, from **sublingual salivary glands** on its undersurface. This enzyme begins the chemical digestion of lipids by breaking down triglycerides, such as those in the pizza's cheese.

bolus A round, soft mass of chewed food within the digestive tract.

papilla Any small, rounded projection extending above a surface.

lingual Relating to speech or the tongue.

The tonsils are the first line of defense against microbes. The **uvula** hangs from the top of the oral cavity at the back of the mouth. This structure functions as a trap door, swinging upward and closing the entrance to the nasal cavity when solid or liquid is forced to the back of the throat. If you try to talk or laugh while eating, the uvula may malfunction and allow food or drink into your nasal passages. The **tonsils**, at the back of the oral cavity, are your first line of defense against any microbes that may enter your mouth along with the pizza. When bacteria invade the oral cavity, the tonsils swell as they attempt to destroy the pathogen through the action of specific immune tissues.

MALT is a disease-prevention tissue. Food is rarely sterile, and yet we almost never suffer disease from ingesting it. Starting with the tonsils, the mucosa of the GI tract contains a disease-prevention tissue called **MALT** (mucosa-associated lymphatic tissue). MALT is also prevalent in the small intestine, large intestine, and appendix. These nodules of lymphatic tissue prevent pathogens from taking over the **lumen** of the digestive tract and are important for preserving homeostasis. MALT tissues represent a large percentage of the entire immune system, including about half of the body's total lymphocytes and macrophages. Without MALT, pathogens could grow within the digestive tract, penetrate the epithelial lining, and cause serious internal infections.

Although MALT is effective, it can be overrun. Bacteria ingested with food suddenly enter a warm, moist, nutrient-rich environment where they can bloom and overwhelm the body's ability to combat them. Often, the acid environment of the stomach will kill these blooming bacteria, but sometimes even that is not enough. If the bacterial colony survives the stomach, the body may flush the entire tract via diarrhea or vomiting to help the immune system rid the body of the invading bacterium.

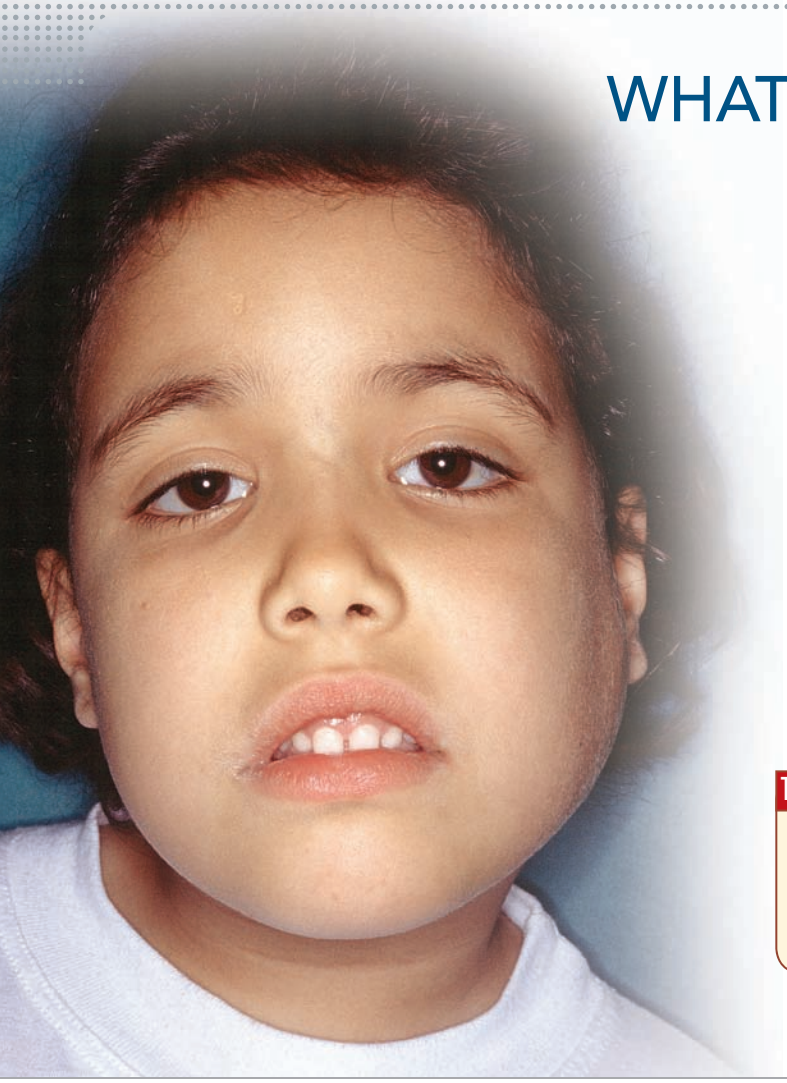
The salivary glands aid in digestion. The **salivary glands** are accessory organs located within the oral cavity. They secrete watery saliva, normally in small quantities to moisten the oral mucosa. As soon as we smell food, the pizza in this instance, salivary production increases. Even the thought of food can increase saliva production. When food is in the mouth, excess saliva is needed to mix with the food and form the slippery bolus required for swallowing.

The major salivary glands are the **parotid** glands, located below and in front of the ears, and the **submandibular** glands under the tongue. A common childhood illness, mumps, is a disease of these glands. Learn more about this disease in *What a Scientist Sees: A Case of the Mumps* on the following page.

The parotid glands produce watery saliva that includes some ions (sodium, potassium, chloride, bicarbonate, and phosphate) and organic substances. The submandibular glands produce thicker, ropey saliva with similar ion content but a larger concentration of mucus. When the sympathetic nervous system is active, watery secretion from the parotid glands is inhibited, whereas the sticky submandibular secretion is not. The result is the familiar "cotton mouth" feeling that we associate with nervousness.

In addition to water and ions, saliva contains **lysozyme**, a **bacteriolytic** enzyme that helps destroy bacteria in the oral cavity. Another important component of saliva is **salivary amylase**, a digestive enzyme that breaks carbohydrate

bacteriolytic Type of agent that lyses or destroys bacteria.



WHAT A SCIENTIST SEES

A Case of the Mumps

Mumps is a painful disease of the salivary glands, usually the parotid glands, causing swelling and a sore throat. The mumps virus is uncomfortable for young children but can cause an inflammation of the brain, pancreas, meninges, testes, or ovaries, especially in older children and adults. In very severe cases, mumps can cause infertility. As we vaccinate more infants, it could become a disease of the past. Mumps is already no longer the global threat it was in the 1950s. It is, however, still a very real problem in the developing world where vaccines are less available.

The largest U.S. outbreak of mumps in three years occurred in New Jersey and New York between August and October 2009. It began in a boys' camp in Sullivan County, New York.

Think Critically

1. How might this outbreak have started, and how did health officials trace it back to this particular camp? Review Chapter 10 for help with this question.
2. Using what you know of the anatomy of the mouth and ears (revisit Chapter 8), can you predict why mumps may lead to deafness?

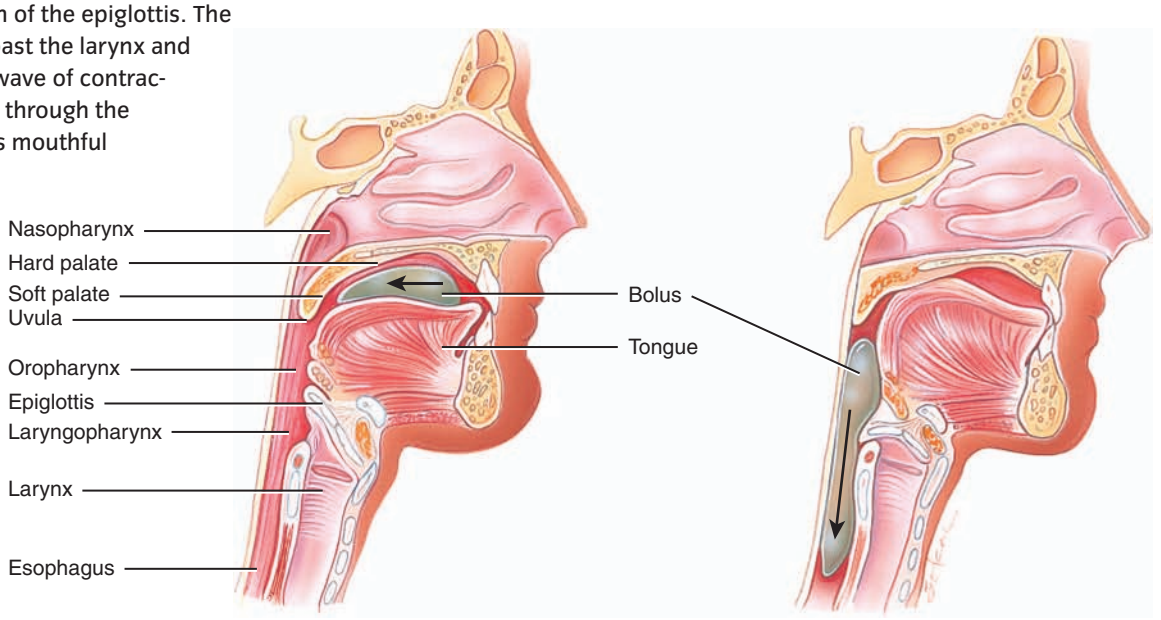
polysaccharides into monosaccharides. Amylase occurs in low levels in saliva and in larger quantities in pancreatic secretions. As we chew the pizza crust, salivary amylase begins breaking the large carbohydrates down into the small monosaccharides that cells can absorb farther down the GI tract.

Deglutition occurs in stages. Swallowing, or **deglutition**, occurs as the bolus of macerated, saliva-mixed pizza is moved to the back of the throat. The tongue positions the bolus at the opening to the esophagus, where you consciously decide to swallow the pizza. This is the last muscular movement you control until the pizza has worked its way to the other end of your GI tract. The tongue is composed of voluntary, consciously controlled skeletal muscle. The muscularis of the GI tract is smooth muscle, controlled by the autonomic nervous system. At the very end of the tract, the anal sphincter is again skeletal muscle.

Swallowing has voluntary and involuntary stages. During the **voluntary stage**, you consciously swallow the pizza. During the **pharyngeal stage**, as seen in Figure 15.5, the bolus involuntarily passes through the pharynx. The epiglottis is closed against the larynx to allow the bolus to bypass the respiratory system and enter the esophagus. It is at this stage that the uvula covers the nasal opening and the larynx moves upward against the epiglottis. The epiglottis covers the opening to the respiratory system, and the bolus slides back toward the esophagus instead of dropping into the respiratory system. Talking while eating can cause the epiglottis to spasm, because it must be opened to allow air to escape in order to vocalize but must be closed to prevent the bolus from sliding into the respiratory tract. Because the epiglottis cannot be opened and closed at the same time, it spasms. Food may drop into the trachea, resulting in choking, and we may require assistance to remove the misplaced bolus.

Swallowing and the pharynx • Figure 15.5

As the bolus of food is swallowed, the larynx moves up, in turn shifting the position of the epiglottis. The bolus of food then slides past the larynx and on to the esophagus. the wave of contraction begun here continues through the entire system, pushing this mouthful into the stomach and eventually on to the remaining organs of the GI tract.



a. Position of structures before swallowing

b. During the pharyngeal stage of swallowing, the tongue presses upward at the back of the mouth. This pulls the larynx up toward the epiglottis, closing the airway to passing food.

The Esophagus Connects the Oral Cavity with the Stomach

The esophagus is a collapsible 20- to 25-centimeter-long conduit that connects the oral cavity with the stomach. Once the bolus of pizza arrives at the top of the esophagus, a peristaltic wave begins. In this third stage of swallowing, the **esophageal stage**, food moves through the esophagus into the stomach via peristalsis. This wave will push the bolus along the esophagus in a controlled manner (neither food nor drink free-fall into the stomach). The esophagus terminates at its lower end with a sphincter muscle. A sphincter muscle is a circular muscle that closes off a tube, functioning like a rubber band pulled tightly around a flexible straw. These muscles appear many times along the GI tract, dividing one organ from the next. The **lower esophageal sphincter** (LES) at the base of the esophagus opens as the pizza bolus touches it, dropping the bolus into the upper portion of the stomach. You can listen to water traveling through the esophagus and hitting the LES if you have a stethoscope. Place the bell of the stethoscope near your xyphoid process, at the base of the sternum, and swallow a mouthful of water. You should be able to count to 10, then hear the water splash against the lower esophageal sphincter. If you are lucky, you might hear the water splash again as it enters the stomach when the LES opens.

The esophagus runs right through the diaphragm at the **esophageal hiatus**. Occasionally, a portion of the upper stomach can protrude through this opening, resulting in a hiatal hernia. This condition can be painful and often requires medical intervention.

CONCEPT CHECK

1. **What** functions does the digestive system perform?
2. **What** are the four layers of the GI tract and the function of each?
3. **What** is the path of food through the organs of the digestive system?
4. **How** is the structure of the esophagus related to the general structure of the digestive tract?

15.2 The Stomach Puts Food to the Acid Test

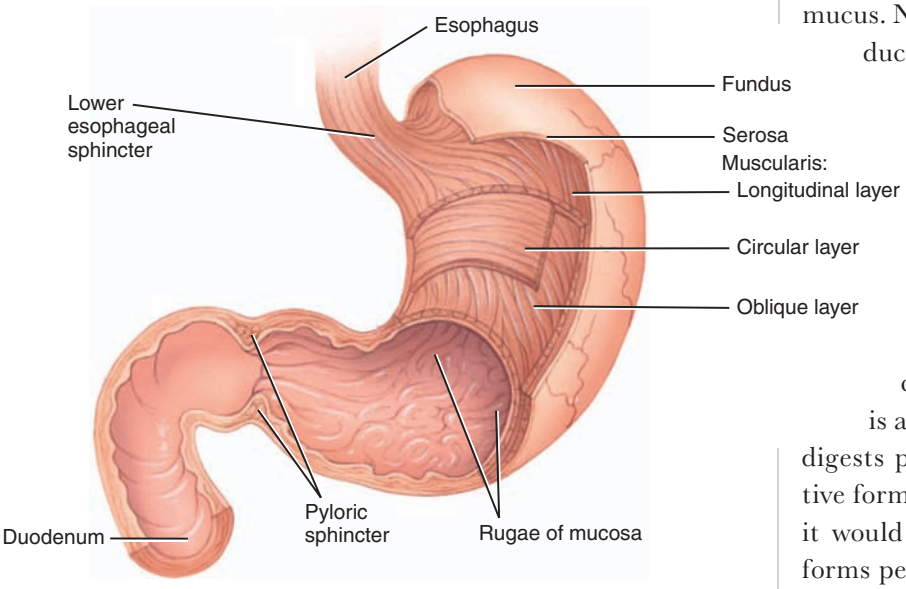
LEARNING OBJECTIVES

1. **Describe** the modifications of the GI tract at the stomach.
2. **List** the phases of digestion in the stomach.

The next organ the pizza encounters in the digestive system is the **stomach**, a J-shaped organ that lies beneath the esophagus. The stomach is separated from the esophagus and the small intestine by two sphincter muscles. The lower esophageal sphincter is the upper boundary of the stomach, and the **pyloric sphincter** marks the lower end of the stomach. The pyloric sphincter, the strongest sphincter muscle of the digestive tract, opens to allow **chyme** to enter the small intestine only when chemically ready. This sphincter is so powerful that it can cause projectile vomiting in infants. The stomach contracts forcefully to push the food into the small intestine, but the pyloric sphincter remains closed until the chyme is fluid enough to be passed on. If the pyloric sphincter refuses to open, the contents of the stomach are instead ejected through the weaker lower esophageal sphincter, leaving the body at impressive speed.

chyme The thick, partially digested fluid in the stomach and small intestine.

The stomach • Figure 15.6



Anterior view of regions of stomach

The GI Tract Has Major Modifications at the Stomach

The typical structure of the gastrointestinal tract undergoes modification at the stomach, as seen in Figure 15.6. The muscularis is usually composed of two layers of muscle, one longitudinal and one circular. The stomach has a third layer of muscle, called the **oblique** layer. The function of the stomach is to churn and mix the bolus of pizza with the acid environment of the stomach and begin protein digestion. The oblique layer helps this churning and mixing. Because the stomach is a holding area for ingested food, it must be able to expand. The walls of the stomach contain folds, or **rugae**, that permit expansion somewhat like a deflated punching ball. Reducing the capacity of the stomach is the subject of *I Wonder… How Does Gastric Bypass Surgery Work?*

The stomach must be protected from itself. A final modification of the stomach is due to the chemical environment in the organ, where the pH is only 2. Such high acidity breaks down large macromolecules and destroys many microbes, but it can also harm the stomach lining. Furthermore, the stomach also secretes enzymes that digest protein, the same compound that the stomach walls are composed of. Therefore, the stomach must be protected from its own contents. The stomach does this by producing a protective layer of thick, viscous, alkaline mucus. Nowhere else does the digestive tract need, or produce, such a mucus coating.

Histologically speaking, the stomach is "the pits." The walls of the stomach contain **gastric** pits, which secrete 2 to 3 quarts of **gastric juice** each day. See Figure 15.7. These pits are composed of **chief** cells and **parietal** cells. The chief cells secrete **pepsinogen** and **gastric lipase**. Pepsinogen is an inactive precursor of the enzyme **pepsin**, which digests proteins and therefore must be secreted in inactive form. (If pepsin itself were produced in stomach cells, it would digest the proteins of those cells.) Pepsinogen forms pepsin only under pH 2. The parietal cells produce **hydrochloric acid** and **intrinsic factor**. The hydrochlo-

gastric Related to the stomach.

I WONDER...

How Does Gastric Bypass Surgery Work?

One of the functions of the stomach is to store the food we eat. Logically, the larger your stomach, the more food you can comfortably store in it. Equally, a smaller stomach would hold less, causing the owner of that stomach to eat smaller portions. Gastric bypass, or bariatric, surgery is a drastic attempt to reduce the stomach capacity of morbidly obese people. This surgery goes by many names stemming from the various methods used to surgically reduce the functional capacity of the stomach. In all cases, gastric bypass surgery results in the lumen of the stomach being divided into a small upper cavity and a larger "remnant" cavity that ingested food does not travel through. Both cavities remain attached to the small intestine, but food can only be stored in the smaller upper pouch.

The surgery itself is difficult, leading to complications within six months in 30% and death in 0.2% of patients. Getting through the surgery is just the first hurdle, as living with a diminished stomach requires a severe restructuring of behaviors and eating habits.

Because the stomach can no longer function normally, diet is strictly regulated, right down to the order in which foods are consumed. Proteins must be eaten first, because digesting them requires time in the stomach. Patients can eat only those foods prescribed by their physician and cannot snack between meals, because eating continuously throughout the day will "bypass the bypass"—no weight reduction will be seen if caloric intake remains high!

ric acid is responsible for the acidic pH of the stomach, which activates pepsin, kills microbes, and denatures ingested proteins. Intrinsic factor is necessary for the absorption of vitamin B_{12}, a micronutrient that helps produce blood cells. Although intrinsic factor is produced in the stomach, it is active in the small intestine.

As the pizza is churned in the stomach, **gastric lipase** will continue the chemical breakdown of fats that began in the mouth. This enzyme specializes in digesting short-chain fatty acids, such as those found in milk, but works at an optimum pH of 5 or 6. In adults, both gastric lipase and lingual lipase have limited roles.

Gastric pits • Figure 15.7

Gastric pits are composed of chief cells and parietal cells. These cells are responsible for creating the specialized environment of the stomach.

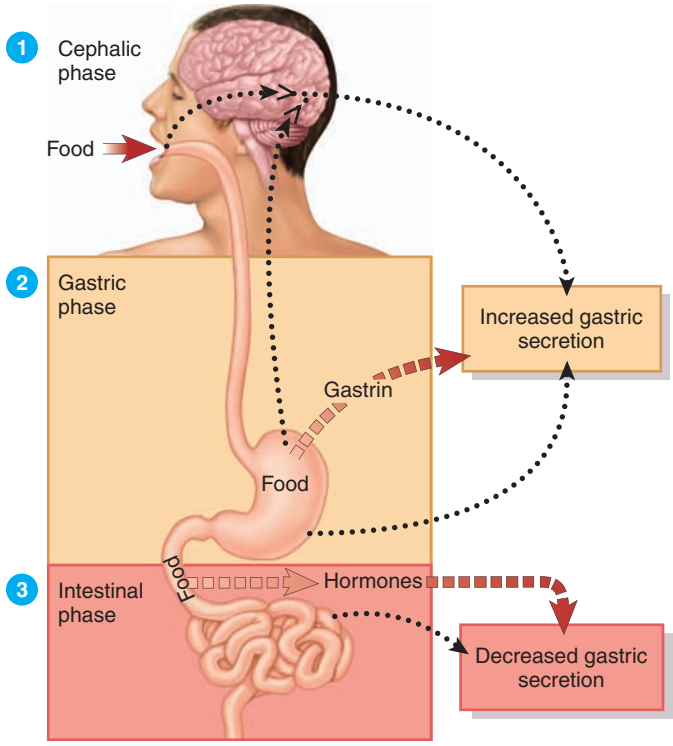
PROCESS DIAGRAM

THE PLANNER

Phases of gastric digestion • Figure 15.8

The activation of the stomach includes three phases.

1. **Cephalic phase**. In the first phase, thoughts of food and the feel of food in the oral cavity stimulate increased secretion from the gastric pits. The stomach begins to churn more actively in preparation for the incoming food.
2. **Gastric phase**. When the bolus reaches the stomach, the second phase of gastric digestion begins. Here the stomach produces gastrin as well as continuing the production of pepsin and HCl. Gastrin aids in stimulation of the gastric pits, providing a feedback system that speeds digestion. Impulses from the stomach also go back to the brain, maintaining contact with the nervous system.
3. **Intestinal phase**. In the final phase of gastric digestion, the chyme begins to leave through the pyloric sphincter. As the chyme leaves the stomach, gastrin production decreases, the impulses to the brain indicate a lessening of chyme, and the brain begins to slow the stimulation of the gastric pits. At the same time, hormones from the beginning portion of the small intestine initiate activation of the small intestine.



In the stomach, the pizza bolus is converted to a pasty, liquid chyme. Pepsinogen is converted to pepsin and digests the proteins of the tomato sauce and the cheese. The low pH assists in denaturing proteins and breaking down the remaining macromolecules, providing an easy substrate for digestion in the small intestine.

The stomach is an active organ. As the bolus of food reaches the stomach, small **mixing waves** are initiated. These waves occur every 15 seconds or so and help to break up the pizza. Even with these mixing waves, the pizza may stay in the **fundus** of the stomach for as long as an hour before being moved into the body of the stomach. There the pizza mixes with the gastric secretions and becomes soupy and thin. The mixing waves of the stomach become stronger, intensifying as they reach the pyloric sphincter. With each wave, a small portion of the chyme is forced through the pyloric sphincter and into the small intestine. The rest of the chyme washes back toward the body of the stomach to be churned further with the next mixing wave.

fundus The portion of any hollow organ that extends above the opening of that organ.

Gastric Digestion Includes Three Phases

Digestion occurs in three phases in the stomach, as seen in Figure 15.8. During the **cephalic phase**, digestion consists of reflexes initiated by the senses. This phase started when you ordered the pizza, intensified as you got out the utensils to eat it, and peaked as you smelled the pizza after delivery. The scents and sounds associated with eating stimulate specific portions of the medulla oblongata, which in turn trigger secretion of the gastric pits. The parasympathetic nervous system is activated, increasing stomach movement. Interestingly, these reflexes can be dampened by stimulation of the sympathetic nervous system. Anger, fear, or anxiety opposes the parasympathetic nervous system, shutting down the cephalic phase and reducing your feelings of hunger.

Once food enters the stomach, stretch receptors and chemoreceptors are activated, initiating the **gastric phase**. Hormonal and neural pathways are set in motion, causing an increase in both gastric wave force and secretion from the gastric pits. As chyme is pushed past the pyloric sphincter, stomach volume decreases and stretch receptors begin to relax. The gastric phase then diminishes in intensity.

The final phase of gastric digestion is the **intestinal phase**. As chyme passes through the pyloric sphincter, intestinal receptors are stimulated. These receptors inhibit the actions of the stomach, causing it to return to rest. At the same time, these receptors stimulate digestion in the small intestine.

Once in the small intestine, the chyme itself stimulates the release of hormones. Chyme containing glucose and fatty acids, such as the chyme from the pizza, causes the release of the hormones **cholecystokinin** (CCK) and **secretin**. CCK inhibits stomach emptying, whereas secretin decreases gastric secretions. Both of these also affect the **liver**, **pancreas**, and **gallbladder**, the accessory organs of the gastrointestinal tract. The combined action of these hormones holds the pizza in the stomach for a prolonged period, ensuring that the pizza is sufficiently broken down, despite its high level of hydrophobic fats.

After two to four hours, the stomach has emptied, and all the chyme has entered the small intestine. Because the pizza has a high fat concentration, it will move rather slowly through the stomach, taking closer to four hours. Had you eaten stir-fried vegetables with their much lower fat content, your stomach would have emptied much more quickly, leaving you feeling hungry again after just a few hours.

The peristaltic wave can be reversed. Sometimes food in the stomach does not "agree" with the stomach because it contains bacteria or toxins that irritate the stomach lining. This situation may cause vomiting. Although not an easy task from a physiological standpoint, reversing the peristaltic wave and churning the stomach violently while holding the pyloric sphincter closed will expel the stomach contents. The esophageal sphincter is weaker than the pyloric sphincter and will open first when the stomach contents are under pressure. The entire contents of the stomach then return through the esophagus and the mouth. The acidity of the stomach is not buffered, causing some burning as the fluid passes the mucous membranes of the mouth and throat. Repeated vomiting can be detrimental to the lining of the mouth as well as the tooth enamel. In addition, replacing the hydrogen ion concentration in the stomach can deplete the hydrogen content of the blood, leading to electrolyte imbalances.

CONCEPT CHECK STOP

1. **Why** is it important that the GI tract is modified at the stomach?
2. **What** are the phases of digestion in the stomach?

15.3 The Intestines and Accessory Organs Finish the Job

LEARNING OBJECTIVES

1. **List** the regions of the small intestine.
2. **Describe** what happens when chyme enters the duodenum.
3. **Explain** the roles of the three major accessory organs and the large intestine.
4. **Discuss** the structure and function of the large intestine.

The pizza's nutrients are now in the small intestine and finally ready for absorption. This organ is the only portion of the GI tube where nutrients are taken into the cells. Prior to reaching the small intestine, the food was cut up, broken down, and denatured. Some enzyme activity was initiated to break down large macromolecules. Here in the small intestine, the nutrients from the pizza are finally absorbed into the body. While the food is in the small intestine, digestion is completed by the accessory organs and is over as the nutrient-depleted chyme passes through the large intestine.

The small intestine • Figure 15.9

THE PLANNER

The cells of the small intestine are the only nutrient-absorbing structures in the digestive system. The larger their surface area, the greater the chances that nutrients taken in with food will be absorbed as they pass through the small intestine. The small intestinal wall has folds upon folds, increasing the surface area immensely.

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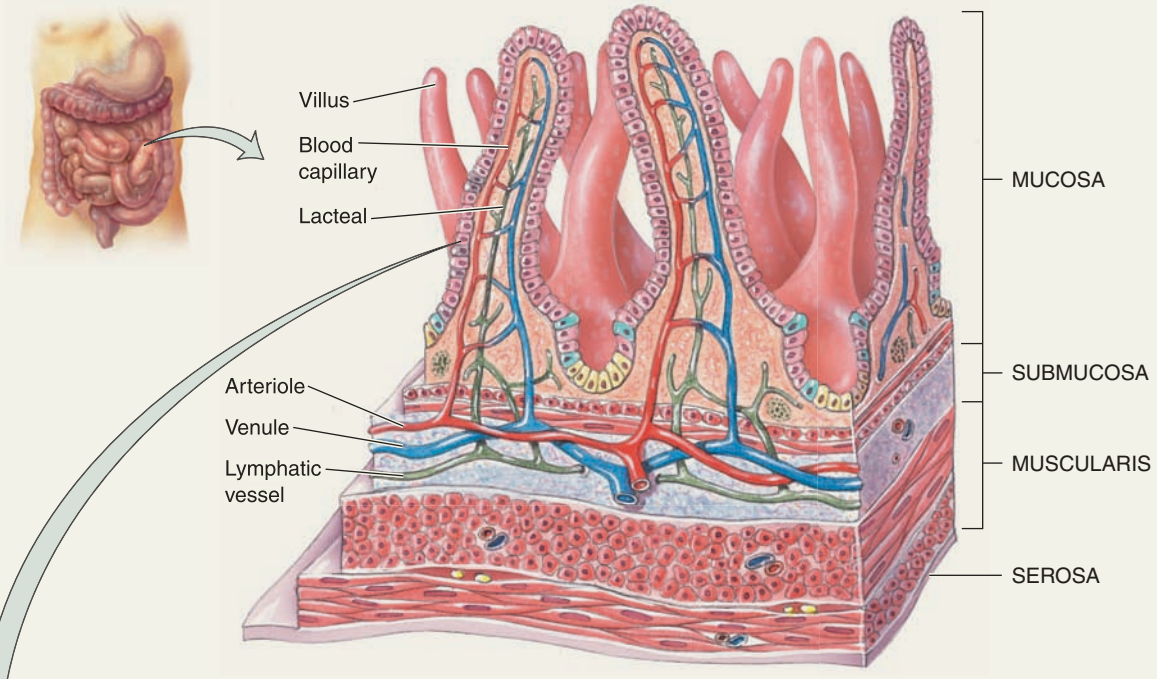
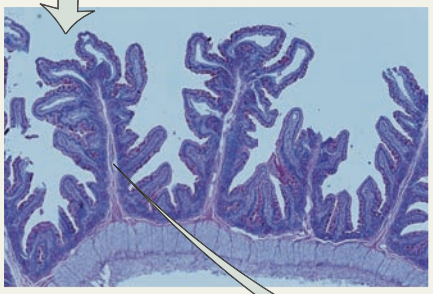
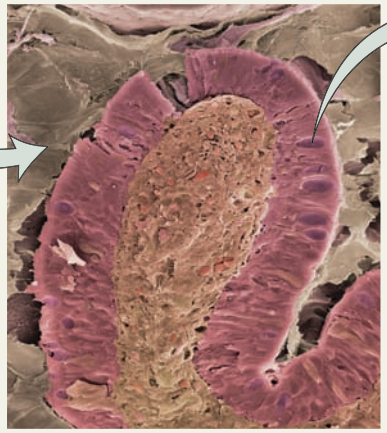


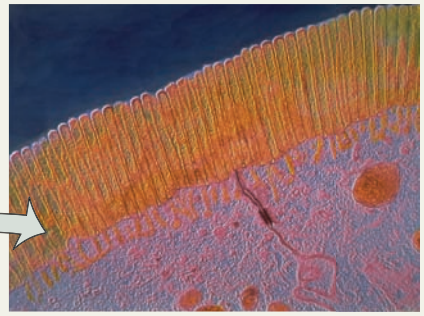
Three-dimensional view of layers of the small intestine showing villi



a. Mucosa
The small intestine is characterized by its velvet-like mucosa. The sole purpose of this organ is to absorb nutrients, requiring a large surface area. The mucosa is folded, and cells are lined with microvilli.



b. Nutrients absorbed by the inner core of the villus are passed into the capillary network or the lymphatic system of the villus' lacteal. Nutrients are often absorbed directly into this lacteal capillary system, which is part of the systemic circulatory system.



c. These microvilli complete the incredibly extensive surface area of the small intestine. Individual cells have hair-like extensions, referred to as the *brush border*, sticking into the lumen to provide large surface area. This brush border facilitates the rapid absorption of nutrients from the lumen of the small intestine.

The Small Intestine Completes the Nutrition Extraction Phase

The small intestine has three regions: the **duodenum**, the **jejunum**, and the **ileum**. The duodenum is the shortest of the regions, extending approximately 25 cm from the pyloric sphincter. The name *duodenum* means 12, reflecting the fact that the region is approximately 12 fingers long. The jejunum encompasses the next 2 meters or so. *Jejunum* means "empty," and this region is characteristically empty during autopsy. The longest portion, the ileum, is about 3.5 in. long. The entire length of the small intestine is 6–7 m, making it the longest digestive organ. This structure is packed into the abdominal cavity by twisting and winding around the central **mesenteries**.

mesenteries Folds in the lining of the abdominal cavity that help to secure the digestive organs.

How large is the surface of the small intestine?

Within the small intestine, the mucosa is shaped into permanent circular folds, which add important surface area to the organ. See **Figure 15.9**. Not only do these folds increase absorption, but they also force the chyme to move in spiral fashion, which creates a longer pathway through the intestine, allowing more time to absorb nutrients.

Because the whole point of this organ is to provide a surface area for absorption, the small intestine has many microscopic projections. The mucosa has finger-like extensions, or **villi**, each one approximately 0.5 to 1 mm long. These villi give the inner surface of the small intestine the look and feel of velvet. Areolar connective tissue is located at the center of each villus. This connective tissue supports an arteriole, a venule, a blood capillary network connecting the two, and a **lacteal**.

Beyond the villi, the small intestine also has **microvilli** on each **apical membrane** of the small intestinal mucosa. These hair-like projections of the cell membrane increase each individual cell's surface area. The microvilli are small and difficult to resolve under a light microscope, where they look like a fuzzy line, not individual structures. The entire surface of the cell is called a **brush border**. Through an electron microscope, scientists have discovered even smaller projections on the surface of these brush borders, which again increase surface area. The total surface area of the small intestine has been variously described as roughly the size of a small backyard or the size of a tennis court (about 260 m^2, or 2,800 ft^2).

apical membrane Membrane at the free end, or top, of the intestinal cells.

The small intestine has an abundance of MALT. The walls of the small intestine are dotted with intestinal glands, which secrete intestinal juice to help digestion. The small intestine also has an abundance of MALT, in the form of **Peyer's patches**. These nodules of lymphatic tissue are akin to tonsils embedded in the intestinal walls. Peyer's patches are an important part of the immune system, protecting the lumen of the digestive tract from bacterial invasion. If even one bacterium escaped the stomach, it could potentially cause serious problems here in the nutrient-rich, warm, moist environment of the small intestine. It is the job of these Peyer's patches to prevent such problems.

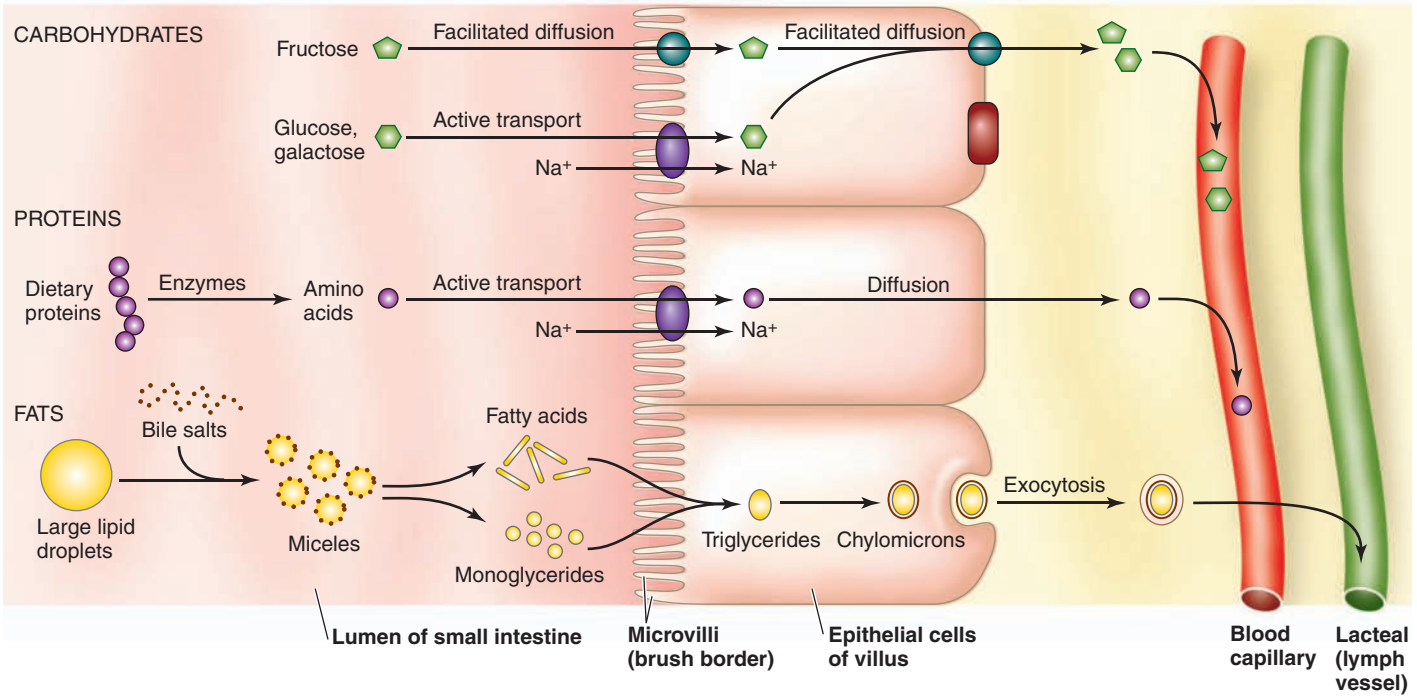
Digestion occurs in the small intestine. Both mechanical and chemical digestion occur in the small intestine. Mechanically, the peristaltic wave is modified into **segmentations** and **migrating motility complexes**. Segmentations are localized mixing contractions that swirl the chyme in one section of the intestine. They allow the chyme to interact with the walls of the small intestine but do not move it along the tract. Migrating motility complexes move the chyme along the length of the small intestine. These movements strengthen as the nutrient level in the chyme decreases.

When soupy chyme enters the duodenum, digestion of proteins, lipids, and carbohydrates has just begun. **Pancreatic juice** is added to the chyme as it enters the small intestine, adding a suite of digestive enzymes that are specific for different macromolecules. For example, **sucrase**, **lactase**, **maltase**, and **pancreatic amylase** all digest carbohydrates.

pancreatic juice The fluid produced by the pancreas and released into the small intestine.

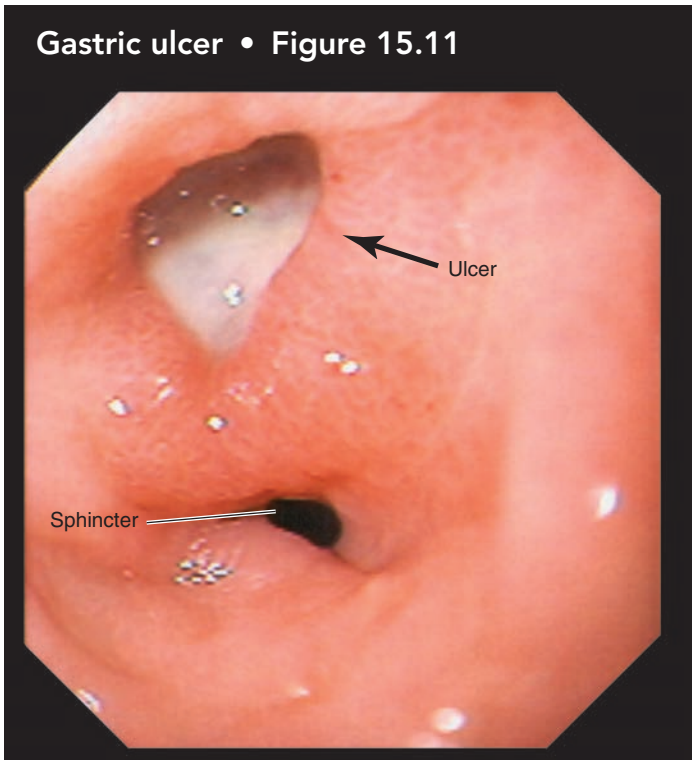
The pH buffers of the pancreatic juice immediately bring the pH of the chyme from 2 (as it was in the stomach) back to 7 in the small intestine, protecting the lining of the duodenum. Raising the pH up to 7 protects the walls of the small intestine; however, it renders pepsin

Digestive activity at the lacteal and intestinal capillaries • Figure 15.10



inactive. Protein digestion continues using **trypsin**, **chymotrypsin**, **carboxypeptidase**, and **elastase**, all secreted from the pancreas. Protein digestion is completed on the exposed edges of the intestinal cells themselves, using the enzymes **aminopeptidase** and **dipeptidase**.

Gastric ulcer • Figure 15.11



In adults, most lipid digestion occurs in the small intestine, because lingual lipase and gastric lipase are barely effective past infancy. **Pancreatic lipase** is the main enzyme causing the breakdown of fats in adults, removing two of the three fatty acids from ingested triglycerides.

In the cells of the small intestine, carbohydrates, short-chain fatty acids, and amino acids are absorbed from the chyme and transported to the capillaries of the lacteal. This process is illustrated in Figure 15.10. Absorbed triglycerides are too large to pass directly into the bloodstream. They are converted to **chylomicrons** and transported in the lymphatic capillary of the lacteal. From here, the fats flow with lymph to the subclavian vein. Once in the bloodstream, **lipoprotein lipase** breaks down chylomicrons to short-chain fatty acids and glycerol.

chylomicrons Small lipoproteins carrying ingested fat from the intestinal mucosa to the liver.

Ulcers are holes in the GI tract. **Ulcers** are open wounds that remain aggravated and painful instead of healing. A gastric or duodenal ulcer is such a wound in the lining of the GI tract, as seen in Figure 15.11. Gastric ulcers occur in the stomach, whereas duodenal ulcers are in the duodenum of the small intestine.

The mucous lining that normally protects the stomach from digestion must be compromised for an ulcer to develop. This can happen when alcohol or aspirin enters the stomach, because these compounds can degrade the mucous lining. Aspirin labels direct you to take the pills with a full glass of water so that they are washed through the stomach or dissolved rather than left sitting on the mucous layer. If the mucous layer is worn away, acidity in the lumen begins to burn the stomach lining, and pepsin will digest proteins of the stomach cells, creating an ulcer. Although in the past ulcers were commonly blamed on stress that caused the release of excess stomach acid, many gastric ulcers are actually caused by infection with *Helicobacter pylori*, a spiral bacterium that thrives in the highly acidic stomach. People who are susceptible to this bacterium often develop gastric ulcers due to bacterial colonies that live on the mucus. Rather than being counseled to reduce their stress level, the old-time ulcer treatment, these patients are given antibiotics to cure their ulcers.

Accessory Organs Help Finish the Job

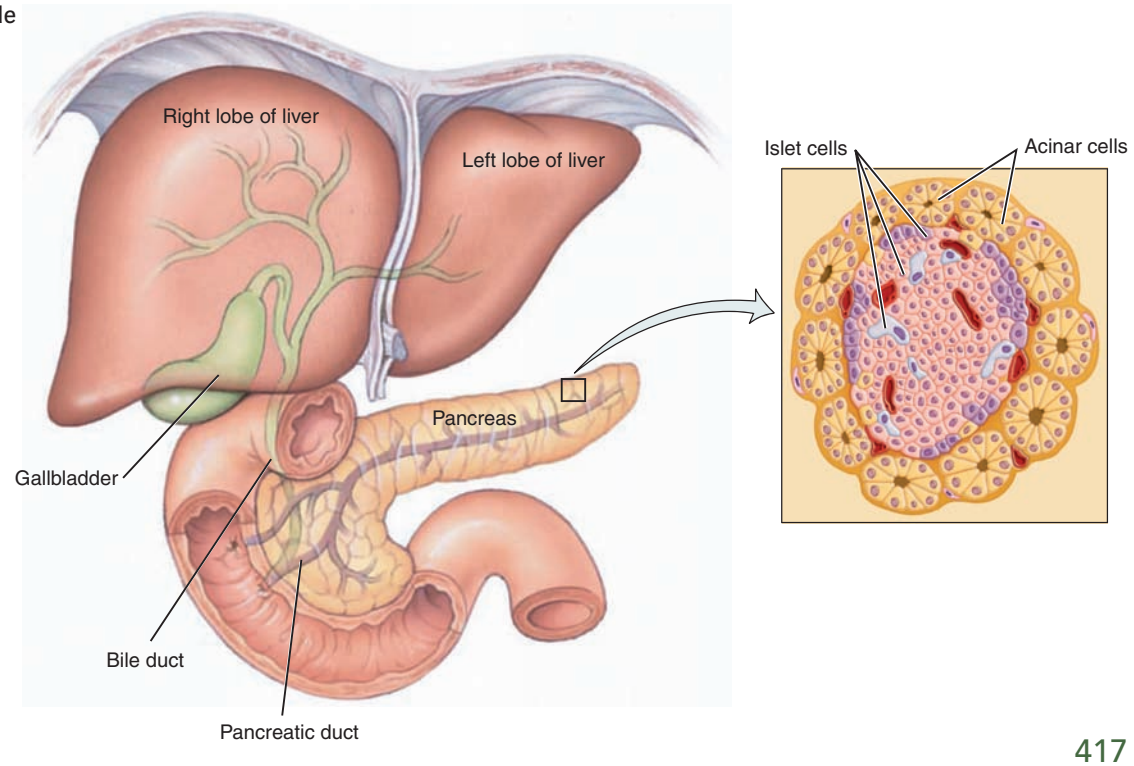
Although the gastrointestinal tract provides both a location for nutrient digestion and the surface required to absorb those nutrients, it cannot complete the job alone. Along the length of the tract several accessory organs assist in digestion, including the pancreas, liver, and gallbladder. See **Figure 15.12**.

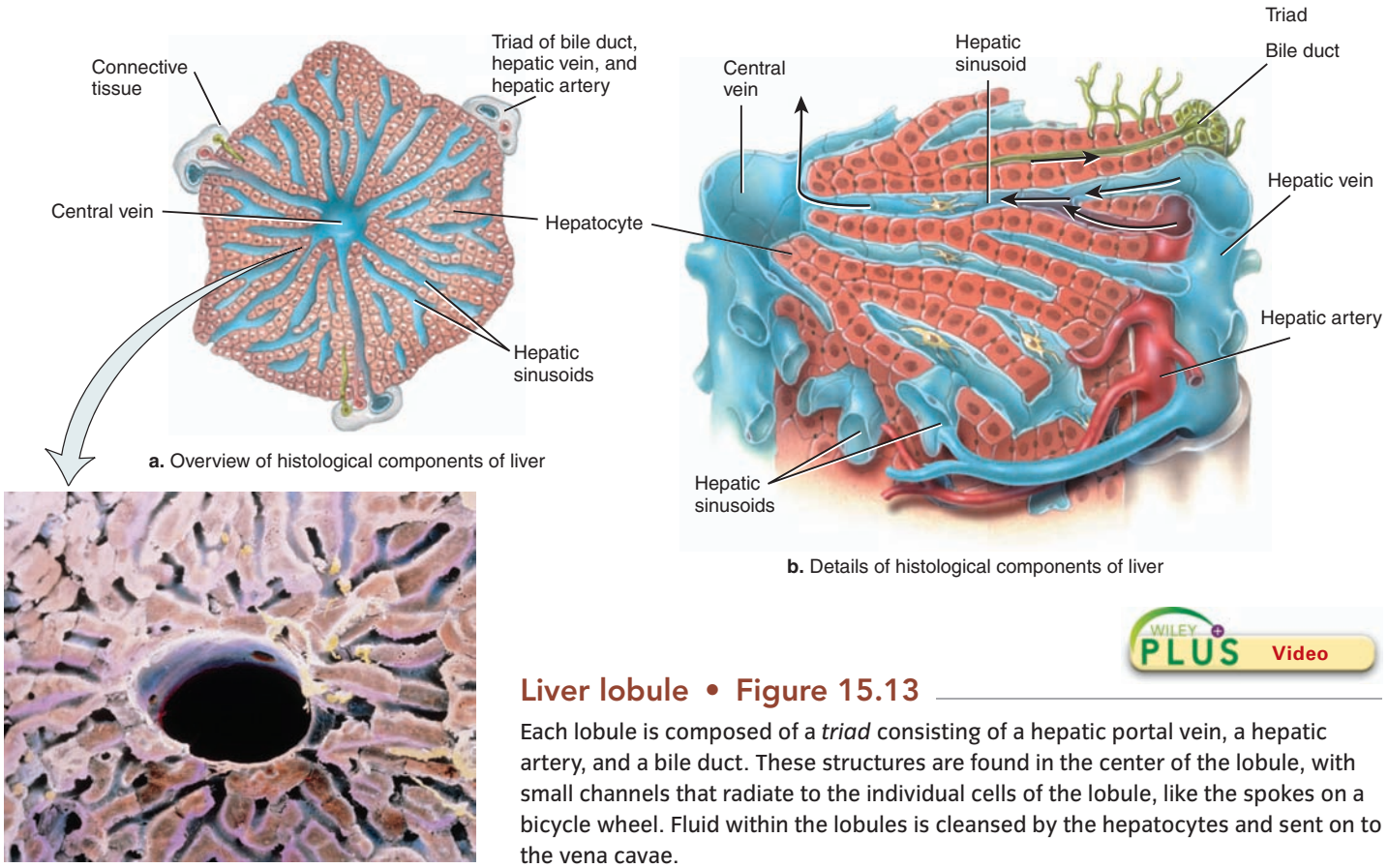
The pancreas is an enzyme factory. The pancreas functions as an exocrine gland in the digestive system, producing enzymes that are released via the **pancreatic duct**. Almost all of the enzymes that act in the small intestine are made in the pancreas. Pancreatic juice also buffers the acidity of the chyme as it leaves the stomach. The small intestine does not have the protective layer of mucus found in the stomach, so it has no protection from the corrosive pH 2 solution being released from the pyloric sphincter. The pancreas secretes pancreatic juice into chyme immediately as it enters the duodenum, largely neutralizing the chyme to safeguard the duodenum from acid burns.

In addition to secreting digestive enzymes into the digestive tract, the pancreas is also responsible for secreting hormones into the bloodstream. The pancreas makes insulin and glucagon, which are responsible for regulating glucose uptake by the cells. Insulin stimulates glucose uptake, whereas glucagon causes glucose to be released into the bloodstream by those muscle and liver cells sequestering it. The cells of the pancreas are described as either cells of the islets of Langerhans or acinar cells. Islet cells function as endocrine cells, secreting insulin and glucagon. Acinar cells produce digestive enzymes.

Major accessory organs • Figure 15.12

The accessory organs include the liver, gallbladder, and pancreas. The acinar cells of the pancreas secrete digestive enzymes into the small intestine via the pancreatic duct.





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Liver lobule • Figure 15.13

Each lobule is composed of a *triad* consisting of a hepatic portal vein, a hepatic artery, and a bile duct. These structures are found in the center of the lobule, with small channels that radiate to the individual cells of the lobule, like the spokes on a bicycle wheel. Fluid within the lobules is cleansed by the hepatocytes and sent on to the vena cavae.

The liver detoxifies what we add to the bloodstream. The liver is the largest organ of the body, aside from the skin, and usually weighs about 1,450 g. The liver has two lobes and sits mostly on the right side of the body. Within the lobes of the liver, the **hepatocytes** are arranged in **lobules**, as seen in Figure 15.13. The lobules are designed to allow maximum contact between hepatocytes and venous blood. The lobules monitor blood collected from the small intestine, adding and subtracting materials to maintain fluid homeostasis.

hepatocytes Liver cells (*hepato* = liver; *cyte* = cell).

The liver is served by a **portal system**. The veins of the small intestine drain into the liver, where they break into capillaries again before being collected into a larger vein and returned to the heart. Blood flows through the digestive organs, travels from arteries to capillaries to veins, and proceeds on to the liver, where it moves back to capillaries, then to the veins that return to the heart. This portal system gives the individual hepatocytes access to the blood coming from the small intestine. This blood includes all absorbed compounds and nutrients, as well as toxins, from the small intestine. The hepatocytes must cleanse the blood before it reaches the heart, removing toxins and storing excess nutrients, such as iron, and fat-soluble vitamins, such as A, D, and E.

Cholesterol, plasma proteins, and blood lipids are manufactured in the hepatocytes. The liver also monitors the glucose level in the blood; when it exceeds 0.1%, hepatocytes remove and store the excess as glycogen. When the glucose level drops, stored glycogen is broken down and released from the hepatocytes, and glucose again rises in the blood.

A diseased liver is a very serious health threat, and unfortunately quite common.

The gallbladder stores and releases bile. **Bile** is formed by the liver as a by-product of the breakdown of hemoglobin and cholesterol. It is stored in the gallbladder, under the right lobe of the liver. Bile salts from the gallbladder are released when fatty chyme is present in the duodenum, such as that from the greasy cheese pizza we have been following throughout this discussion. The concentrated bile salts act as an **emulsifier** or biological detergent, breaking larger fat globules into smaller ones. Bile aids in fat digestion by increasing the surface area on which the digestive activities of pancreatic lipase can act. Bile, therefore, is another form of mechanical digestion.

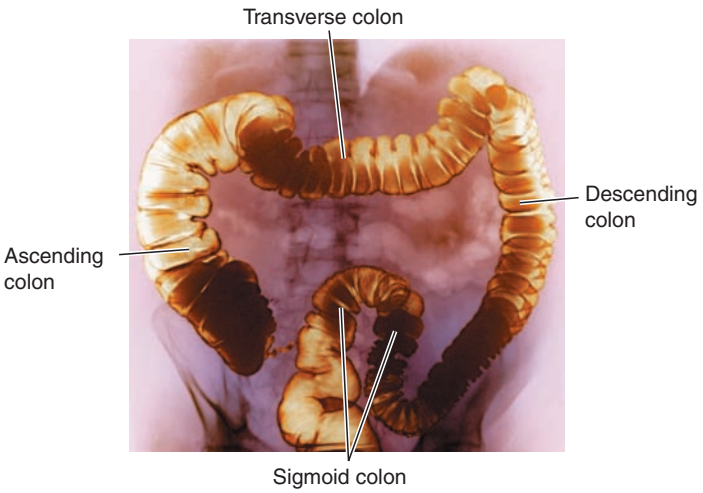
Stones can form in bile. A small, condensed crystal of cholesterol that forms in the gallbladder may attract calcium ions from the concentrated bile, resulting in the formation of a stone. Stones can grow big enough to get stuck in the bile duct when the gallbladder releases its contents. This causes pain and blocks the flow of bile. The gallbladder is often removed if stones are a chronic problem. After removal of the gallbladder, bile is still produced by the liver but not stored. The patient should not eat fatty meals, because there is no store of bile to aid in lipid digestion. See *Health, Wellness, and Disease: Gallbladder Removal Options* for more information.

The Large Intestine Absorbs and Reabsorbs

Once the pizza that we ate hours ago reaches the end of the small intestine, the body cannot pull any more nutrients from it. The chyme now passes from the small intestine into the next portion of the GI tract, the large intestine. See **Figure 15.14**. The overall function of the

Large intestine • Figure 15.14

The four parts of the colon can be easily seen in this image. A substance was given to the patient that reflects X-rays. Exposure to X-rays then provides a clear view of the colon. The ascending colon is on the left, the large horizontal loop is the transverse colon, and the very densely stained descending colon runs along the right side. The sigmoid colon makes its characteristic "S" turn at bottom center.



HEALTH, WELLNESS, AND DISEASE

Gallbladder Removal Options

Occasionally the gallbladder will malfunction. It can become swollen and inflamed, or it may develop calcareous stones in the stored bile, or tumors or polyps may grow inside the walls of the gallbladder. In each case, bile will usually accumulate in the gallbladder, causing pressure and irritation. The gallbladder may also harbor a bacterial infection or burst as more and more bile is produced.

Removal of the gallbladder is the most common surgical solution to any gallbladder problem. There are two types of removal surgery, laparoscopic or open cholecystectomy. The Latin prefix for the gallbladder is *cholecyst-*, therefore a cholecystectomy is the removal (*-ectomy*) of the gallbladder. Laparoscopic surgery is far less invasive than open surgery. Small incisions are made in the skin, and a thin lighted laparoscope is inserted into the distended belly of the patient. The organs of the abdominal cavity are separated by filling the cavity with carbon dioxide. Small tools are inserted into the distended cavity, and using the light and camera of the laparoscope, the gallbladder is located. The blood vessels, nerves, and ducts attaching the gallbladder to the liver and duodenum are cut and sutured. The free organ is then removed from the body, along with any health problems it may carry. Open cholecystectomy is a more involved surgery, requiring a large incision in the skin and often at least one overnight stay in the hospital. The abdominal cavity is opened, the lobes of the liver are pushed aside, and the gallbladder is exposed. Using scalpels, tissue clamps, retractors, sutures, and other common surgical tools, the gallbladder is removed. Open cholecystectomy is performed during emergency gallbladder removal, as it requires less patient preparation and less time to remove the diseased organ. As expected, recovery is more difficult from open surgery than from laparoscopy, and the scars are far larger.

large intestine is to reabsorb the water that was added to the chyme to begin digestion. Along with the water, the large intestine absorbs many dissolved minerals and some vitamins. The valve that makes the transition from the ileum of the small intestine to the **cecum** of the large intestine is called the **ileocecal valve**. The ileum joins the large intestine a few centimeters from the bottom. The cecum hangs below the junction, forming a blind pouch that ends in the **vermiform appendix**.

The rest of the large intestine is the colon. The remainder of the large intestine is commonly called the **colon**. The four divisions of the colon describe the direction of flow within them:

- The **ascending colon** runs up the right side of the abdominal cavity.
- The **transverse colon** cuts across the top of the abdominal cavity, underneath the stomach.
- At the left side of the abdominal cavity, the colon turns back down, in the **descending colon**.
- At the lower left of the abdominal cavity, the colon makes an S turn to wind up in the center of the body. This turn is called the **sigmoid colon** and is the portion of the colon where feces may sit for long periods of time before moving out the rectum.

polyp Growth protruding from a mucous membrane.

Often, **polyps** can develop in the colon as feces rest against the mucosa.

The walls of the large intestine have **haustra**, pouches created by strands of muscle in the walls. These pouches fill with undigested material, which moves from pouch to pouch via **mass movements**.

Diarrhea results from an irritation of the colon. The chyme moves through the colon far too quickly for water or minerals to be absorbed. Medicines that prevent mass movements are often helpful in slowing the movement of chyme through the large intestine, giving the walls of the organ ample time to return the excess water to the bloodstream. To combat severe diarrhea, remedies that contain minerals and fluid are ingested to replace what is lost in the diarrhea.

The last 20 cm of the colon are the **rectum** and **anus**. Chyme remains in the colon for 3 to 10 hours, during which time it becomes progressively drier. Compacted chyme is called feces. When feces enter the upper portion of the rectum, they trigger the opening of the internal anal sphincter, a smooth muscle. The feces move into the rectum and press against the external anal sphincter. This pressure triggers **defecation**, a skeletal muscle action. As with all skeletal muscles, control over defecation is voluntary. On average, by age two and a half children are mature enough to control defecation.

Material moves through the large intestine in mass movements, created using a peristaltic wave. In the colon, water is reabsorbed from the soupy chyme, concentrating the waste material and conserving fluid. As the water is pulled back into the bloodstream across the lining of the colon, so too are minerals and vitamins. The removal of water leaves undigested remains of food and fiber in the colon, as well as bacteria, such as *E. coli* and other **obligate anaerobes** that naturally live in the large intestine. These colonies are necessary in the colon because they break down indigestible material and often produce essential vitamins. Sometimes these colonies can be embarrassing because they generate gas when fermenting solids.

obligate anaerobes Bacteria that require an oxygen-free environment.

The appendix may play a role in the immune system. Although the function of the appendix is unclear, it may play a role in the immune system. Some have suggested it is a structure that at some point in our evolution was used to store the "good" bacteria our bodies need along the length of the colon.

When the appendix acts up, we get **appendicitis**, which presents as pain near the belly button that migrates to the lower right side. Other symptoms include nausea, vomiting, low fever, constipation or diarrhea, inability to pass gas, and abdominal bloating. The abdomen becomes increasingly tender, and simple movements cause pain. These are all symptoms of a blockage in the appendix that prevents normal flow through the organ. Feces may be blocking the entrance, or lymph nodes in the surrounding walls may be swollen due to infection. In either instance, the contents of the appendix cannot move, leading to a buildup of pressure, decreased blood flow, and inflammation. If the pressure is not relieved quickly, the entire organ can rupture or suffer **gangrene**. For unknown

gangrene Tissue death due to lack of blood flow.

Summary of the functions of the digestive organs Table 15.1

Organ	Functions
Mouth	See other listings in this table for the functions of the tongue, salivary glands, and teeth, all of which are in the mouth. Additionally, the lips and cheeks keep food between the teeth during mastication, and buccal glands lining the mouth produce saliva.
Tongue (accessory structure)	Maneuvers food for mastication, shapes food into a bolus, maneuvers food for deglutition, detects taste and touch sensations.
Salivary glands (accessory structure)	Produce saliva, which softens, moistens, and dissolves foods; cleanses mouth and teeth; and initiates the digestion of starch and lipids.
Teeth (accessory structure)	Cut, tear, and pulverize food to reduce solids to smaller particles for swallowing.
Pharynx	Receives a bolus from the oral cavity and passes it into the esophagus.
Esophagus	Receives a bolus from the pharynx and moves it into the stomach. This requires relaxation of the upper esophageal sphincter and secretion of mucus.
Stomach	Mixing waves macerate food, mix it with secretions of gastric glands (gastric juice), and reduce food to chyme. Gastric juice activates pepsin and kills many microbes in food. Intrinsic factor aids absorption of vitamin B_{12}. The stomach serves as a reservoir for food before releasing it into the small intestine.
Pancreas (accessory structure)	Pancreatic juice buffers acidic gastric juice in chyme (creating the proper pH for digestion in the small intestine), stops the action of pepsin from the stomach, and contains enzymes that digest carbohydrates, proteins, triglycerides, and nucleic acids.
Liver (accessory structure)	Produces bile, needed for emulsification and absorption of lipids in the small intestine; detoxifies blood containing absorbed nutrients and other substances.
Gallbladder (accessory structure)	Stores and concentrates bile and releases it into the small intestine.
Small intestine	Muscular contractions mix chyme with digestive juices; migrating motility complexes propel chyme toward the ileocecal sphincter; digestive secretions from the small intestine, pancreas, and liver complete the digestion of carbohydrates, proteins, lipids, and nucleic acids; circular folds, villi, and microvilli increase surface area for absorption; site where nutrients are absorbed.
Large intestine	Churning, peristalsis, and mass movements drive the contents of the colon into the rectum; bacteria produce some B vitamins and vitamin K; absorption of water, ions, and vitamins; defecation.

reasons, most cases of appendicitis occur in people ages 10 to 30. As soon as inflammation is diagnosed, the appendix is surgically removed to prevent it from rupturing and releasing pathogens into the intestine or the abdominal cavity.

See **Table 15.1** for a sunmary of the organs involved in digestion.

CONCEPT CHECK

1. **What** are the regions of the small intestine?
2. **What** happens when chyme enters the duodenum?
3. **What** are the major functions of the pancreas, liver, and gallbladder?
4. **How** does the structure of the large intestine differ from that of the small intestine?

15.4 Digestion Is Both Mechanical and Chemical

LEARNING OBJECTIVES

1. **Define** mechanical and chemical digestion.
2. **List** the major enzymes of chemical digestion, and note their substrates.
3. **Discuss** the general role of the digestive system.
4. **Describe** the regulation of the digestive system.

Throughout this look at the digestive system, we have discussed various organs and their contribution to the process of digestion. Now it's time to summarize, so that we can view digestion as one continuous process.

Digestion is the breaking down of food into substances that can be absorbed and used by the body. This is accomplished through two processes: mechanical digestion and chemical (or enzymatic) digestion. **Mechanical digestion** refers to the chopping, cutting, and tearing of large pieces of food into smaller ones. Bites of apple, for example, are crushed and torn into pieces in your mouth, but these pieces are still recognizable as apple pieces, and no chemical alteration has occurred. The pieces have all the properties and chemical bonds of the original apple, but with a larger surface area needed for chemical digestion.

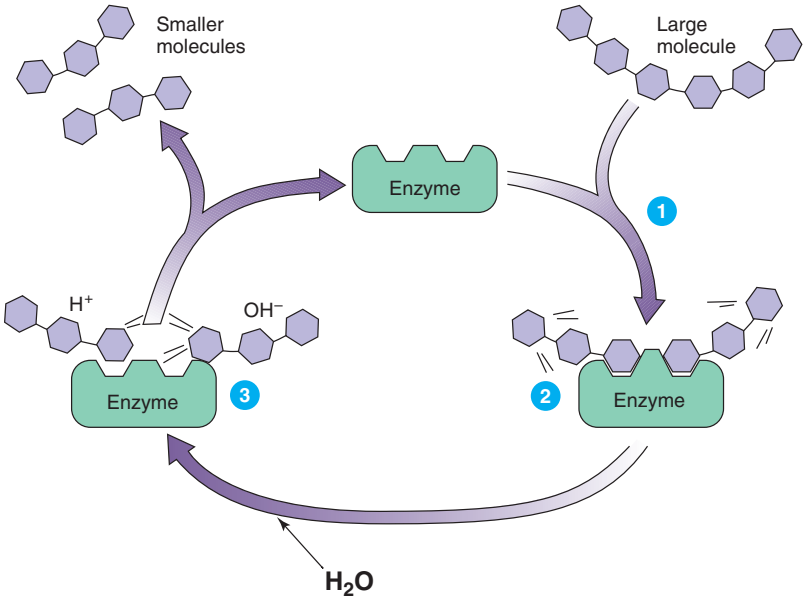
Mechanical digestion occurs mainly in the mouth. Once the bolus of food is passed to the esophagus, a small amount of mechanical digestion occurs in the stomach, as it rolls and churns the food into chyme. The chyme then moves through the pyloric sphincter into the duodenum, where large droplets of fat are emulsified via bile. The action of bile is a form of mechanical digestion, breaking larger fat droplets into smaller ones without altering the chemical structure of the fats. At this point, the chyme is ready for enzymatic degradation, and mechanical digestion is finished.

Unlike Mechanical Digestion, Chemical Digestion Alters Chemical Bonds

Most of the food we ingest is composed of **polymers**, long chains of repeating subunits, which our digestive enzymes must break into short chains, or monomers. It is these shorter units that are absorbed in the small intestine and used to produce the proteins and energy needed for survival.

In order to digest our myriad foodstuffs, we need several digestive enzymes. See **Figure 15.15**. As you know, enzymes are functional proteins that work best under a set of optimal conditions of pH, temperature, substrate, and product levels. (The substrate is the compound the enzyme acts upon, and the product is the result of that enzymatic

Hydrolase activity • Figure 15.15



Most of our digestive enzymes are **hydrolases**, meaning that they catalyze the breakdown of large polymers by inserting water molecules between monomers. We unconsciously know that digesting requires water, because we find it uncomfortable to eat without drinking.

1. Large molecule of food enters the digestive system.
2. Enzyme binds to food (substrate) molecule.
3. Enzyme uses H_2O to split the substrate molecule, leaving an OH^- on one product molecule and an H^+ on the other.

action.) All enzymes are specific for a particular substrate and catalyze only one reaction.

Enzyme names are usually built from the name of the substrate, followed by the suffix "-ase." It is easy to predict the function of an enzyme simply by evaluating its name. For example, lipase digests lipids, and nucleases digest nucleic acids. The major digestive enzymes, along with their substrates, products, and sources, are listed in Table 15.2.

Digestive enzymes Table 15.2

Enzyme	Source	Substrates	Products
Saliva			
Salivary amylase	Salivary glands	Starches (polysaccharides)	Maltose (disaccharide), maltotriose (trisaccharide), and α-dextrins
Lingual lipase	Lingual glands in the tongue	Triglycerides (fats and oils) and other lipids	Fatty acids and diglycerides
Gastric Juice			
Pepsin	Stomach chief cells	Proteins	Peptides
Gastric lipase	Stomach chief cells	Triglycerides (fats and oils)	Fatty acids and monoglycerides
Pancreatic Juice			
Pancreatic amylase	Pancreatic acinar cells	Starches (polysaccharides)	Maltose (disaccharide), maltotriose (trisaccharide), and α-dextrins
Trypsin	Pancreatic acinar cells	Proteins	Peptides
Chymotrypsin	Pancreatic acinar cells	Proteins	Peptides
Elastase	Pancreatic acinar cells	Proteins	Peptides
Carboxypeptidase	Pancreatic acinar cells	Amino acid at carboxyl end of peptides	Amino acids and peptides
Pancreatic lipase	Pancreatic acinar cells	Triglycerides (fats and oils) that have been emulsified by bile salts	Fatty acids and monoglycerides
Nucleases			
Ribonuclease	Pancreatic acinar cells	Ribonucleic acid (RNA)	Nucleotides
Deoxyribonuclease	Pancreatic acinar cells	Deoxyribonucleic acid (DNA)	Nucleotides
Brush Border			
α-Dextrinase	Small intestine	α-dextrins	Glucose
Maltase	Small intestine	Maltose	Glucose
Sucrase	Small intestine	Sucrose	Glucose and fructose
Lactase	Small intestine	Lactose	Glucose and galactose
Enterokinase	Small intestine	Trypsinogen	Trypsin
Peptidases			
Aminopeptidase	Small intestine	Amino acid at amino end of peptides	Amino acids and peptides
Dipeptidase	Small intestine	Dipeptides	Amino acids
Nucleosidases and phosphatases	Small intestine	Nucleotides	Nitrogenous bases, pentoses, and phosphatases

All digestive enzymes, except for salivary amylase and pepsin, act in the small intestine. Salivary amylase begins to digest carbohydrates in the mouth and continues in the bolus of food entering the stomach. Pepsin, found in the stomach, works best at pH 2. The rest of the digestive enzymes operate best at pH 7 and are found inside the small intestine.

The Digestive System's Job Is to Prepare Nutrients

For some organisms, locating and ingesting nutrients is relatively simple. The single-celled **amoeba** oozes through the environment, constantly searching for nutrients. When it runs across a bit of organic material, the amoeba engulfs the particle and brings it into its body via **phagocytosis**. Once inside the amoeba, the particle is broken into its building blocks by digestive enzymes in the lysosome. Monosaccharides are released from carbohydrates, amino acids are released from proteins, and small carbon compounds are released from fatty acids. These small organic compounds are then used by the amoeba to generate essential enzymes, cellular structures, and energy. Micronutrients are obtained by the amoeba in a similar fashion, via **pinocytosis**. Often, micronutrients are released from larger compounds during lysosomal digestion.

amoeba A single-celled organism that moves using pseudopods (false feet formed by oozing a portion of the body forward).

The human body is far more complex than the amoeba, but each cell still needs nutrients in order to survive. Interestingly, human cells absorb nutrients in exactly the same manner as the amoeba: through diffusion, osmosis, facilitated diffusion, and active transport (including both phagocytosis and receptor-mediated endocytosis). However, the cells cannot leave their positions in the tissues to ooze through the environment in search of nutrients. Although that would make a wonderful B-movie plot, our cells must remain organized and in position! Therefore, the digestive system's job is to prepare nutrients for circulation through the blood, which reaches every cell.

Those nutrients, of course, vary with the food the digestive system gets to work on. In addition, the food we eat has local and even global importance. See *Ethics and Issues: How Much Do We Help the World If We Go Vegan?*

Regulation of Our Digestive Activities Is Based on Blood Sugar Levels

Normally, blood sugar is kept at approximately 70 to 110 mg glucose per 100 ml of blood. This level is essential to keep neurons functioning. When blood glucose drops, we feel hungry. If we eat, blood sugar levels rise from the absorption of ingested glucose. If we do not eat, we begin to break down glycogen stores, where excess glucose has been stored in liver and skeletal muscles. Glycogen can break down to glucose relatively quickly. Fats and proteins can also be converted to glucose, but at a higher energy expense. During starvation, the protein of skeletal muscle, and even heart muscle, is broken down to provide glucose for the brain, as described in the coverage of the general adaptation syndrome in Chapter 9.

CONCEPT CHECK

1. **How** does mechanical digestion differ from chemical digestion?
2. **What** are the major enzymes of chemical digestion and **what** molecules does each one digest?
3. **What** is the general role of the digestive system?
4. **What** happens when blood glucose drops? **What** happens to our blood sugar when we eat? **When** we don't eat?

ETHICS AND ISSUES

How Much Do We Help the World If We Go Vegan?

With the global population surging toward 7 billion, we have to wonder: Can the world feed itself? With food prices fluctuating (and usually rising), how many more hundreds of millions will be hungry if we don't solve inequities in both food production and food distribution?

It takes up to 10 calories of grain to produce 1 calorie of meat. Could it help to eat more grain directly instead of feeding it to animals? Yes, say vegetarians and vegans, who argue that eating meat is wrong on a number of levels. (Vegetarians eat no meat, but may use leather or eat dairy products, while vegans consume no animal products in any way.) Eating vegetable matter puts a person lower on the food chain and so uses available energy more efficiently. In theory, if people ate and digested the food needed to raise one cow to maturity, that food would satisfy many more people than could receive dietary satisfaction from the one cow.

However, the situation is more complicated than that. A large proportion of meat comes from animals that are raised partly or wholly on rangeland. Our digestive systems are not built to break down the cellulose in grasses, therefore grasses are not available to us as food. In this sense cattle expand, not contract, our food supply.

In any case, the trend in world food consumption is veering away from vegetarianism: More livestock and poultry are being eaten. Meat consumption is rising faster in the newly developing world, and in many cultures eating meat is a sign of wealth. In addition, meat does provide a source of protein and micronutrients, and our digestive systems are equipped to handle the full absorption of both.

Critical Reasoning Issues Some political leaders have derided energy conservation as only a sign of "personal virtue" and not a real force in the larger world. Vegetarianism is, as we have seen, a form of energy conservation—or is it?

Think Critically

1. Do you see a strong or weak connection between your personal actions and their consequences for your community and larger society?
2. Explore the analogy between vegetarianism and energy conservation. How are they the same and how are they different?
3. According to recent studies of China's changing dietary demands with increasing cultural affluence, an affluent diet will use three times as much grain as a typical vegetarian diet. How might cultural practices affect the understanding of the "grain feeds more people" argument in other countries?

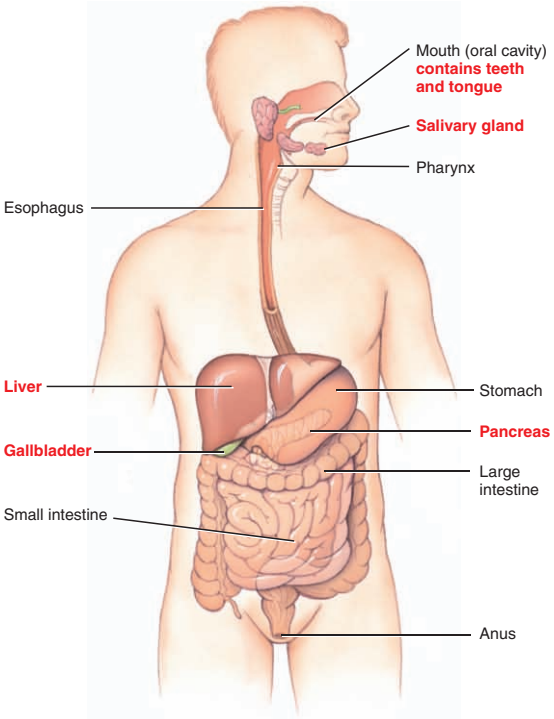
Summary

THE PLANNER

1 Digestion Begins in the Oral Cavity 404

- The digestive system ingests food, mixes and propels that food through the digestive organs, mechanically and chemically breaks down the food, absorbs nutrients from the food, and releases the undigested wastes. The digestive system, or GI tract, is one continuous tube, divided by sphincter muscles. Each organ has anatomical alterations that allow it to perform a specific function. As shown here, the organs, in order, are the oral cavity, esophagus, stomach, small intestine, large intestine, and rectum. Accessory organs, including the salivary glands, liver, gallbladder, and pancreas, assist in digestion.

Figure 15.1



Right lateral view of head and neck and anterior view of trunk

- The salivary glands, located within the oral cavity, secrete watery saliva, normally in small quantities to moisten the oral mucosa.
- The esophagus is a collapsible 20- to 25-cm-long conduit that connects the oral cavity with the stomach.

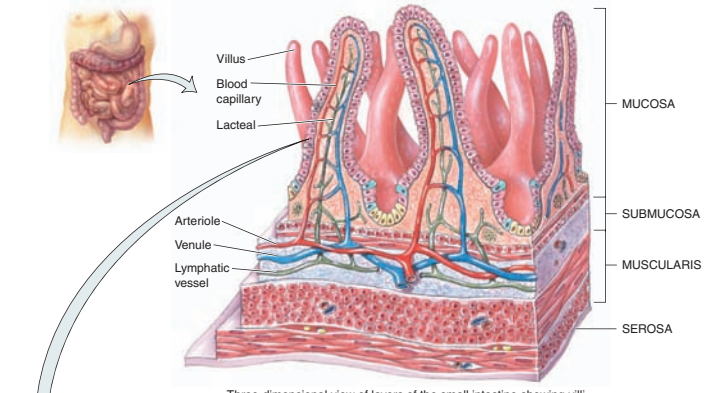
2 The Stomach Puts Food to the Acid Test 410

- The stomach is separated from the esophagus and the small intestine by two sphincter muscles. The lower esophageal sphincter is the upper boundary of the stomach, and the pyloric sphincter marks the lower end of the stomach.
- In the stomach, a **bolus** is converted to a pasty, liquid **chyme**.
- Digestion occurs in three phases in the stomach. During the cephalic phase, digestion consists of reflexes initiated by the senses. In the gastric phase, the bolus reaches the stomach, and the stomach produces gastrin as well as continuing the production of pepsin and HCl. In the final phase of gastric digestion, the intestinal phase, the chyme begins to leave through the pyloric sphincter.

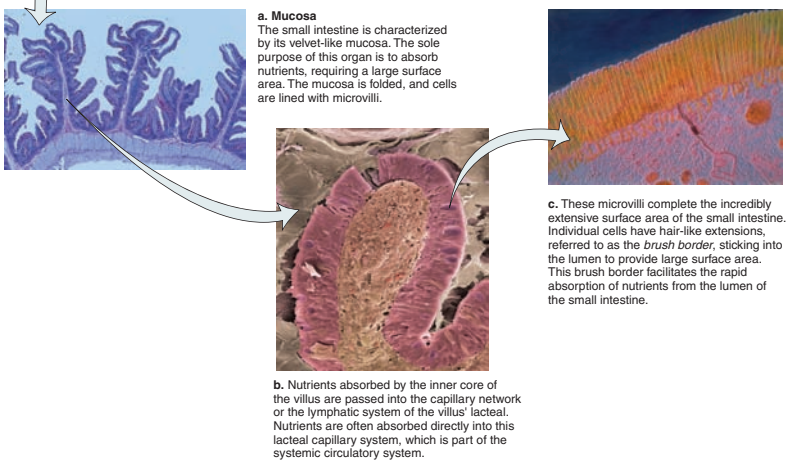
3 The Intestines and Accessory Organs Finish the Job 413

- The small intestine has three regions: the duodenum, the jejunum, and the ileum.
- Because the whole point of the small intestine is to provide a surface area for absorption, it has many microscopic projections, as seen in the figure.

Figure 15.9



Three-dimensional view of layers of the small intestine showing villi



a. Mucosa
The small intestine is characterized by its velvet-like mucosa. The sole purpose of this organ is to absorb nutrients, requiring a large surface area. The mucosa is folded, and cells are lined with microvilli.

b. Nutrients absorbed by the inner core of the villus are passed into the capillary network or the lymphatic system of the villus' lacteal. Nutrients are often absorbed directly into this lacteal capillary system, which is part of the systemic circulatory system.

c. These microvilli complete the incredibly extensive surface area of the small intestine. Individual cells have hair-like extensions, referred to as the *brush border*, sticking into the lumen to provide large surface area. This brush border facilitates the rapid absorption of nutrients from the lumen of the small intestine.

- The liver cleanses the blood as it drains from the small intestine. The gallbladder stores and releases bile. The pancreas produces digestive enzymes and buffers that control the pH of the digesting chyme in the small intestine.

4 Digestion Is Both Mechanical and Chemical 422

- **Mechanical digestion** starts in the mouth, where the teeth grind and crush the food. Saliva moistens the food, forming a bolus that can be swallowed.
- Muscular contractions push the bolus through the esophagus into the stomach, where high acidity starts to break it down. This acidity kills most pathogens but can attack the stomach wall if the mucous lining is damaged.
- In the small intestine, enzymes continue to break down the material called chyme. Macromolecules are absorbed through the highly convoluted lining of the small intestine and into the blood supply. As the now-nutrient-depleted chyme moves through the large intestine, water is removed. The waste material, including a large proportion of harmless bacteria, is moved into the rectum and excreted.

Key Terms

- amoeba 424
- apical membrane 415
- bacteriolytic 407
- bolus 407
- chemical digestion 406
- chylomicrons 416
- chyme 410
- fundus 412
- gangrene 420
- gastric 410
- hepatocytes 418
- lingual 407
- macerated 406
- mechanical digestion 406
- mesenteries 415
- obligate anaerobes 420
- pancreatic juice 415
- papilla 407
- peristaltic wave 405
- polyp 420

Critical and Creative Thinking Questions

1. Starting at the esophagus, trace the pathway of food through the system. At each organ, indicate anatomical adaptations to the general GI tract tube structure that enhance the specific functions of that organ.
2. One of the more drastic solutions for overeating is to "staple" the stomach, a procedure called gastric bypass surgery. This surgery reduces stomach size, preventing it from holding as much. How would this affect the functioning of the stomach? What essential hormone decreases in the blood as the surface area of the stomach decreases?
3. Give a brief review of the structure of a liver lobule. Explain why cirrhosis of the liver can lead to jaundice and eventual liver failure. What exactly prevents the liver lobule from functioning?
4. **CLINICAL CLICK QUESTION**
   Edith was sitting at the Thanksgiving table, talking with her grandchildren. Suddenly she experienced a sharp, persistent pain in her chest. Edith felt as if she were having a heart attack, but with no history of heart problems, she reasoned that was not the case. Her meal had been quite rich, with heavy fatty foods drenched in gravy. After lying down for a few minutes, Edith's pain subsided. When she visited her doctor he talked with her about heartburn.

   What causes heartburn? How might antacids assist in treatment of heartburn?

After subjecting Edith to a barium X-ray, her doctor discovered that a portion of her stomach was protruding through the diaphragm where it comes through to the stomach. The stomach extending above the diaphragm was pinched and swollen. The stomach had literally slid upward into the chest cavity through the esophageal opening. This type of organ displacement is called a hernia.

Why is this particular hernia a cause for concern? What might happen to the stomach if this is not corrected? What procedure might correct Edith's hiatal hernia? For help with this diagnosis, visit Http://www webmd.com/heratburn-gerd/hiatal-hernia.

What is happening in this picture?

Ah, we have all been in this situation. Approximately 15 to 20 minutes after eating a large meal, we are overcome by a feeling of total relaxation and comfortable fatigue. What sounds best at times like these is a nap. This sort of behavior is expected, especially after meals that include a large dose of turkey—a meal high in proteins that induce sleepiness. This reaction to food is so well understood that we often subconsciously avoid certain foods when we need to maintain a wakeful state, rather than eat a heavier meal and then fight to stay awake during our next appointment or class.

Think Critically

1. In which organ of the digestive tract is that heavy meal as you begin to feel drowsy?
2. What digestive processes are occurring while you rest? Is there something about these processes that allows them to function better while you are at rest?
3. Is there a correlation between the type of meal that you ingest and these sleepy feelings? If so, what is that relationship?

Self-Test

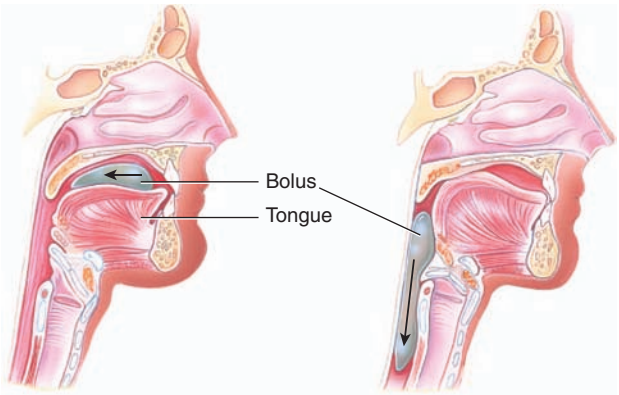
1. The correct order of layers in the GI tract from external surface to lumen is _____.
   a. serosa, muscularis, submucosa, mucosa
   b. mucosa, submucosa, serosa, muscularis
   c. muscularis, submucosa, mucosa, serosa
   d. submucosa, mucosa, muscularis, serosa

2. The muscularis of the GI tract is responsible for _____.
   a. protecting the lumen
   b. creating the peristaltic wave
   c. absorbing water and nutrients
   d. allowing the tract to slide around inside the abdominal cavity

3. The teeth responsible for grinding and crushing are the _____.
   a. incisors
   b. canines
   c. premolars
   d. All types of teeth grind food.

4. Immune defenses in the digestive system include all of the following EXCEPT _____.
   a. MALT
   b. Peyer's patches
   c. liver
   d. tonsils

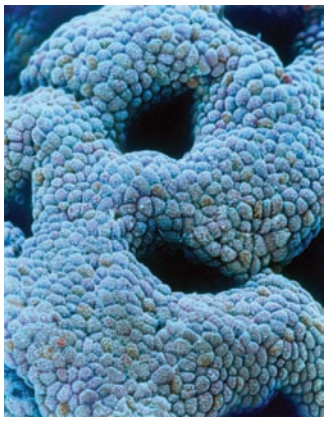
5. The stage of swallowing that involves the rising of the larynx is shown in this figure as _____.
   a. A
   b. B



A B

6. One function of the organ containing the structures seen below is _____.

a. chemical digestion of carbohydrates
b. mechanical digestive action of bile
c. chemical digestion of proteins
d. nutrient absorption



7. The organ that is responsible for producing digestive enzymes is the _____.

a. liver
b. gallbladder
c. pancreas
d. sublingual salivary gland

8. Most stomach ulcers are caused by _____.

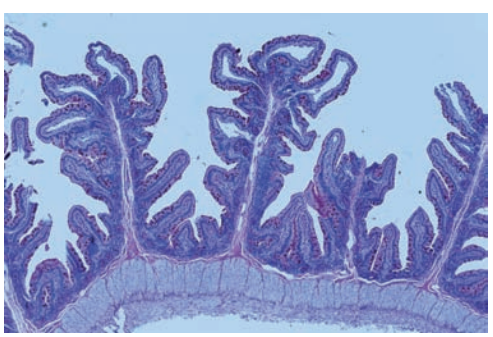
a. stress
b. aspirin eroding the mucous lining of the stomach
c. alcoholism
d. a spiral bacterium

9. The phase of gastric digestion that is initiated simply by the smell of food is the _____.

a. cephalic phase
b. gastric phase
c. intestinal phase
d. All three phases are triggered by the smell of food.

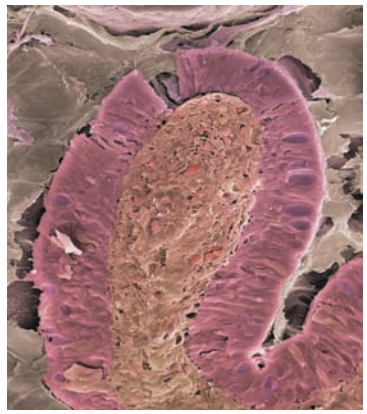
10. The function of the organ containing the structures shown below is to _____.

a. chemically digest food
b. mechanically digest food
c. absorb nutrients
d. All of the above are true of this organ.



11. The structure shown below is found in the _____ and serves to _____.

a. large intestine/decrease surface area
b. small intestine/increase surface area
c. stomach/produce HCl
d. liver/produce and store bile



12. The most common viral liver disease in the United States is _____.

a. hepatitis A
b. hepatitis B
c. hepatitis C
d. All three are equally uncommon.

13. The cecum and the vermiform appendix are part of the _____.

a. small intestine
b. Peyer's patch immune tissues
c. liver
d. large intestine

14. Chemical digestion destroys chemical bonds, creating more surface area for continued digestion.

a. True
b. False

15. All of the following digestive enzymes function at a pH of 7 except _____.

a. pepsin
b. trypsin
c. amylase
d. lingual lipase

THE PLANNER

Review your Chapter Planner on the chapter opener and check off your completed work.

16 The Urinary System

The object of the contest was to determine who could drink the most water without going to the bathroom. Admittedly, many thought this an odd contest, but no one expected it to be fatal. Unfortunately, humans can die from drinking too much water over a short period of time, and that is exactly what happened to one contestant in this competion. She did in fact drink herself to death. The medical term for this fatal over-hydration is acute dilutional hyponatremia. The term hyponatremia indicates that the sodium ions in the interstitial fluid and blood are suddenly diluted to a level far below homeostatic range. Although not common, hyponatremia is most often seen in marathon runners and other endurance athletes who mistakenly over-hydrate after a grueling event. Symptoms of over-consumption of water include confusion, severe headache, disorientation, nausea, and vomiting. If left undetected, severe hyponatremia can lead to serious neurological symptoms, including seizure, coma, and death. As fluid sodium levels drop below the normal range (132–144 mmol/liter), symptoms of water intoxication begin. When the sodium ion concentration in the extracellular fluid of the brain drops below 105 mmol/liter, water begins to move from the surrounding fluid into the neurons of the brain. As the neurons swell with excess water, confusion and drowsiness set in. It is the rate of change in sodium levels that causes death—if the sodium levels are diluted very quickly over a short period of time, as in this ill-fated contest, death can result.

CHAPTER OUTLINE

The Kidneys Are the Core of the Urinary System 432

- The Kidneys Are Filtering Organs
- Nephrons Do the Filtering Work

Urine Is Made, Transported, and Stored 436

- Glomerular Filtration Is the First Step in Urine Formation
- Tubular Reabsorption Recycles Water to the Blood
- Tubular Secretion Removes Products from the Blood
- Urine Is Transported to the Bladder for Storage
- The Urethra Transports Urine out of the Body
- Incontinence Is the Loss of Control over Voiding

The Urinary System Maintains the Body's Fluid and Solute Balance 442

- The Urinary System Maintains the Body's Water–Salt Balance
- The Kidneys Help Maintain the Blood's Acid–Base Balance

Life-Threatening Diseases Affect the Urinary System 446

- Warning Signals from Urinalysis
- Kidney Disease Is Life Threatening

CHAPTER PLANNER

- ❑ Study the picture and read the opening story.
- ❑ Scan the Learning Objectives in each section:
  p. 432 ❑ p. 436 ❑ p. 442 ❑ p. 446 ❑
- ❑ Read the text and study all figures and visuals. Answer any questions.

Analyze key features

- ❑ Biological InSight, p. 433
- ❑ Process Diagram, p. 436
- ❑ I Wonder..., p. 437
- ❑ What a Scientist Sees, p. 444
- ❑ Ethics and Issues, p. 447
- ❑ Health, Wellness, and Disease, p. 449
- ❑ Stop: Answer the Concept Checks before you go on:
  p. 435 ❑ p. 442 ❑ p. 445 ❑ p. 449 ❑

End of chapter

- ❑ Review the Summary and Key Terms.
- ❑ Answer the Critical and Creative Thinking Questions.
- ❑ Answer What is happening in this picture?
- ❑ Answer the Self-Test Questions.

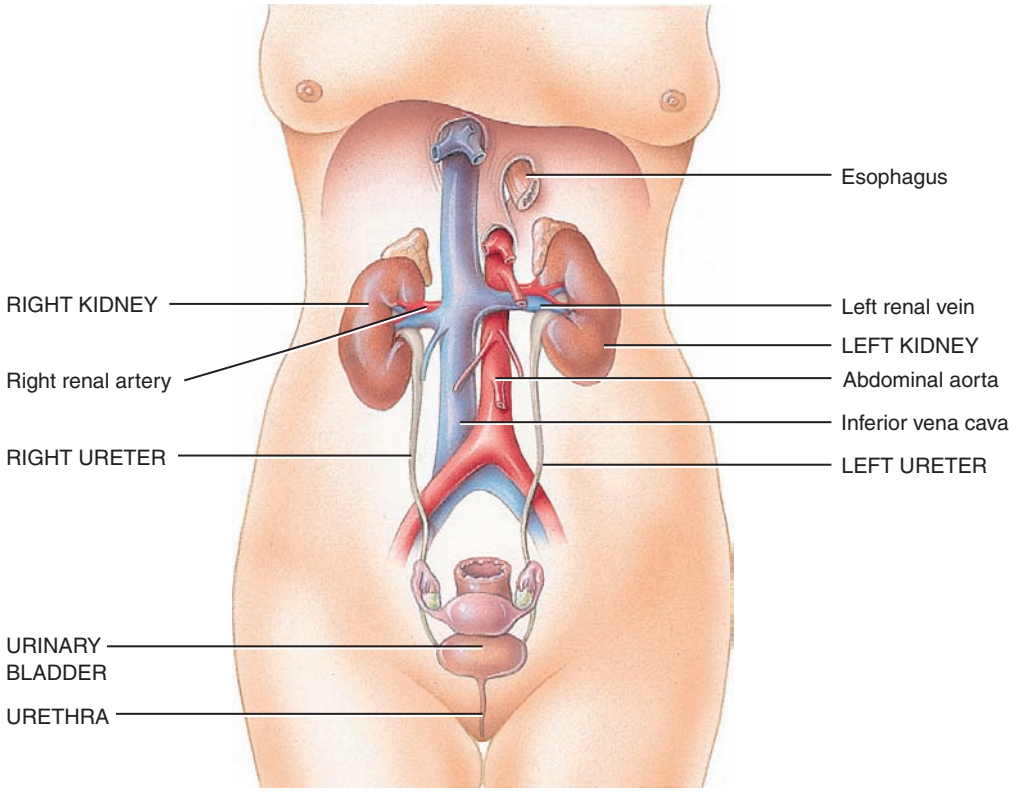
16.1 The Kidneys Are the Core of the Urinary System

LEARNING OBJECTIVES

1. **Define** the functions of the urinary system.
2. **Identify** the organs of the urinary system.
3. **Diagram** the anatomy of the kidney and the nephron.

The urinary system excretes aqueous waste as it maintains fluid balance and blood volume. It also regulates blood composition, helps to maintain blood pressure, monitors and maintains red blood cell levels, and assists in vitamin D synthesis. In addition, the urinary system is responsible for monitoring and adjusting the ionic composition of the blood, regulating the pH of the blood, regulating blood volume, maintaining blood glucose levels, and producing hormones that regulate calcium levels. It does all this with four organs: pairs of kidneys and ureters, the urinary bladder, and the urethra. See **Figure 16.1**.

Listing all of these functions at once, it becomes obvious that the four organs of the urinary system are responsible for regulating the fluid environment of the body. As a whole, these are such vital functions that if the urinary system fails, the body will shut down within a few days. Urine is not the goal of the urinary system, but rather is formed as a by-product of the system's functions. All waste materials removed from the blood by the urinary system leave the body in urine.



Anterior view

Urinary system • Figure 16.1

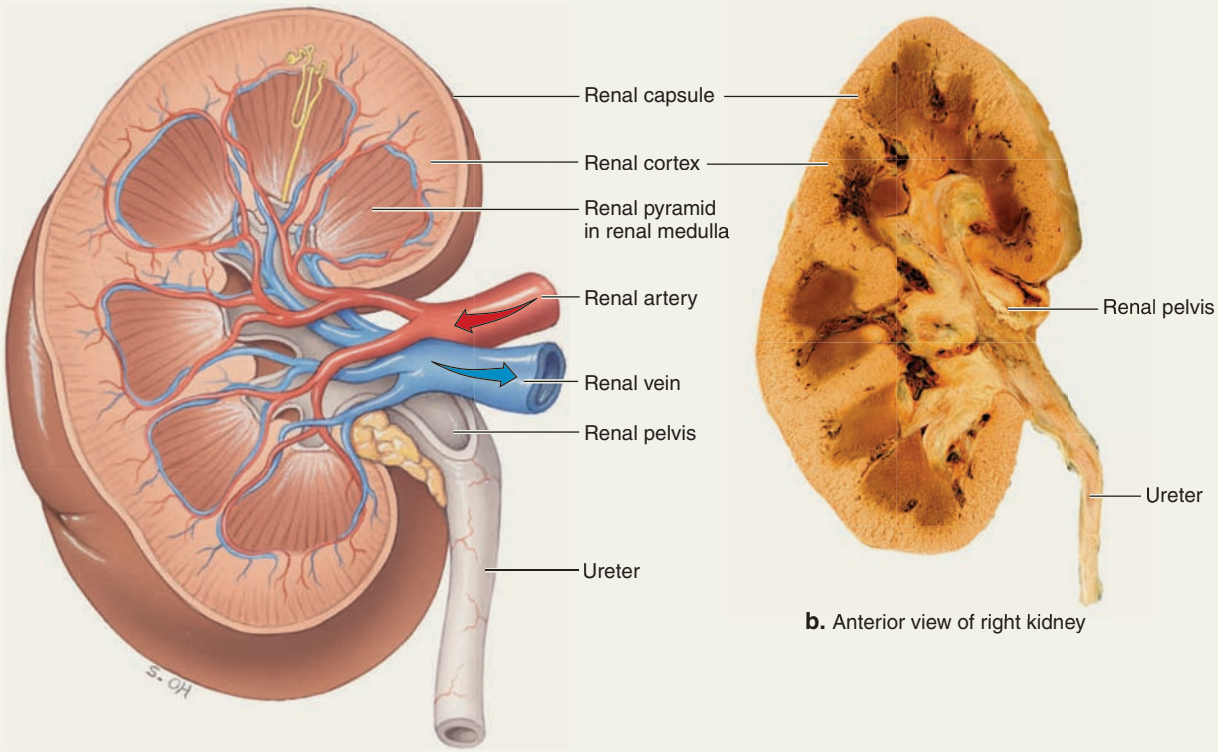
The urinary system lies behind the peritoneum, protected by strong back muscles and fat. The kidneys are the organs responsible for filtering the blood, whereas the other three organs—ureters, urinary bladder, and urethra—transport and excrete the resulting urine.

Biological InSight

The kidney • Figure 16.2

THE PLANNER

The renal cortex contains a large blood supply, and it is here that filtration occurs. Blood enters the kidneys via the renal artery, and filtered blood leaves through the renal vein. The renal medulla is involved in the fine-tuning of this filtrate, and the renal pelvis transports the final waste product, the urine, from the kidneys to the ureters.



a. Frontal section of right kidney

b. Anterior view of right kidney

The Kidneys Are Filtering Organs

The kidneys filter blood and produce hormones. These two fist-sized, bean-shaped organs lie immediately beneath the back musculature, embedded in a protective layer of fat. The kidneys are retroperitoneal, meaning they lie posterior to the peritoneal membrane. Because of this relatively unprotected placement, the kidneys are susceptible to injury from an external blow. Consequently, football pads are designed to cover the kidney area, and boxers are not permitted to punch opponents in the back. Due to the placement of the liver, the right kidney is slightly lower than the left.

The kidneys themselves are covered with a tough outer membrane, the renal capsule. See Figure 16.2. A large renal artery enters the kidney at the **hilus**. One quarter of the blood from every heartbeat gets shunted through the renal arteries to the kidneys. The hilus provides exit for the equally large renal vein, the kidney's nerves and lymphatic vessels, and the ureter.

A sagittal section through a kidney reveals a uniform outer cortex and an irregular inner medulla. The cortex appears grainy and solid, and portions of it dip between the **renal pyramids** of the medulla. The renal pyramids are cone-shaped structures formed from an accumulation of collecting ducts draining formed urine from the renal cortex to the renal pelvis. The **renal pelvis** is the area adjacent to the hilus, and is where urine is collected and passed to the ureters. The renal pelvis is coated in a protective mucous membrane because it contains toxic urine. Among other substances, this urine contains **nitrogenous wastes** filtered from the blood.

nitrogenous wastes Compounds containing nitrogen, such as urea, that are produced during protein metabolism.

Blood flow through the kidneys is highly structured and regulated. A full quarter of the blood flow from each heartbeat is sent to the kidneys rather than to the body tissues. Blood flowing through the kidneys takes a long and circuitous route:

1. Blood enters the kidneys via the renal artery.
2. The renal artery branches into the segmental arteries that supply each renal pyramid of the kidneys, and these segmental arteries give rise to the interlobular arteries that dive between renal pyramids.
3. The interlobular arteries then take the blood to the renal cortex, where it is further divided into afferent arterioles, efferent arterioles, and capillaries. Recall that afferent means "arriving" and efferent means "exiting." In this case, afferent arterioles arrive at the filtering unit,while efferent arterioles exit the filtering unit, or glomerulus.
4. Filtered blood winds its way through the kidney via the efferent arterioles, where it moves to capillaries and is then collected by the interlobular veins. From here, the pathway reverses, moving through interlobular and segmental veins, and finally leaving the kidneys through the renal vein.

The kidneys also produce hormones. Beyond cleaning blood, the kidneys also produce the hormones calcitriol and erythropoietin, which regulate the concentration of calcium and formed elements in blood. Calcitriol, the active form of vitamin D, helps maintain blood calcium levels. Erythropoietin stimulates production of new red blood cells.

Nephrons Do the Filtering Work

nephron The filtering unit of the kidney.

The kidneys can be composed of a million or more **nephrons**, packed together under the renal capsule. When observing a kidney under a light microscope, it becomes obvious that the organ is in fact a large collection of these small nephrons, each responsible for filtering a portion of the blood that passes through the kidney.

The large blood supply that enters the kidneys is diverted through ever-smaller arteries and arterioles until it winds its way to a knotted vessel at the beginning of each nephron. That vessel knot is called a **glomerulus**, formed from an incoming arteriole. A **glomerular capsule** (also called Bowman's capsule) surrounds the glomerulus. See **Figure 16.3**. The blood vessel leaving each nephron then breaks into **peritubular capillaries**, which wind around the entire nephron before collecting into venules and eventually the renal vein. This capillary bed surrounds the nephron, as shown in Figure 16.3. It is here that the urinary and cardiovascular systems are linked. The nephron is the site of blood filtration, where the wastes are removed and the necessary ions and nutrients are returned to the circulatory system.

peritubular capillaries Capillaries that surround the nephron (*peri* = around; *tubular* = nephron tubules).

The waste material filtered into Bowman's capsule remains in the fluid within a second part of the nephron: the tubule. The nephron's tubule has three sections:

- the **proximal convoluted tubule** (PCT)
- a loop called the **nephron loop** or the **loop of Henle**
- a **distal convoluted tubule** (DCT) connected to a collecting duct

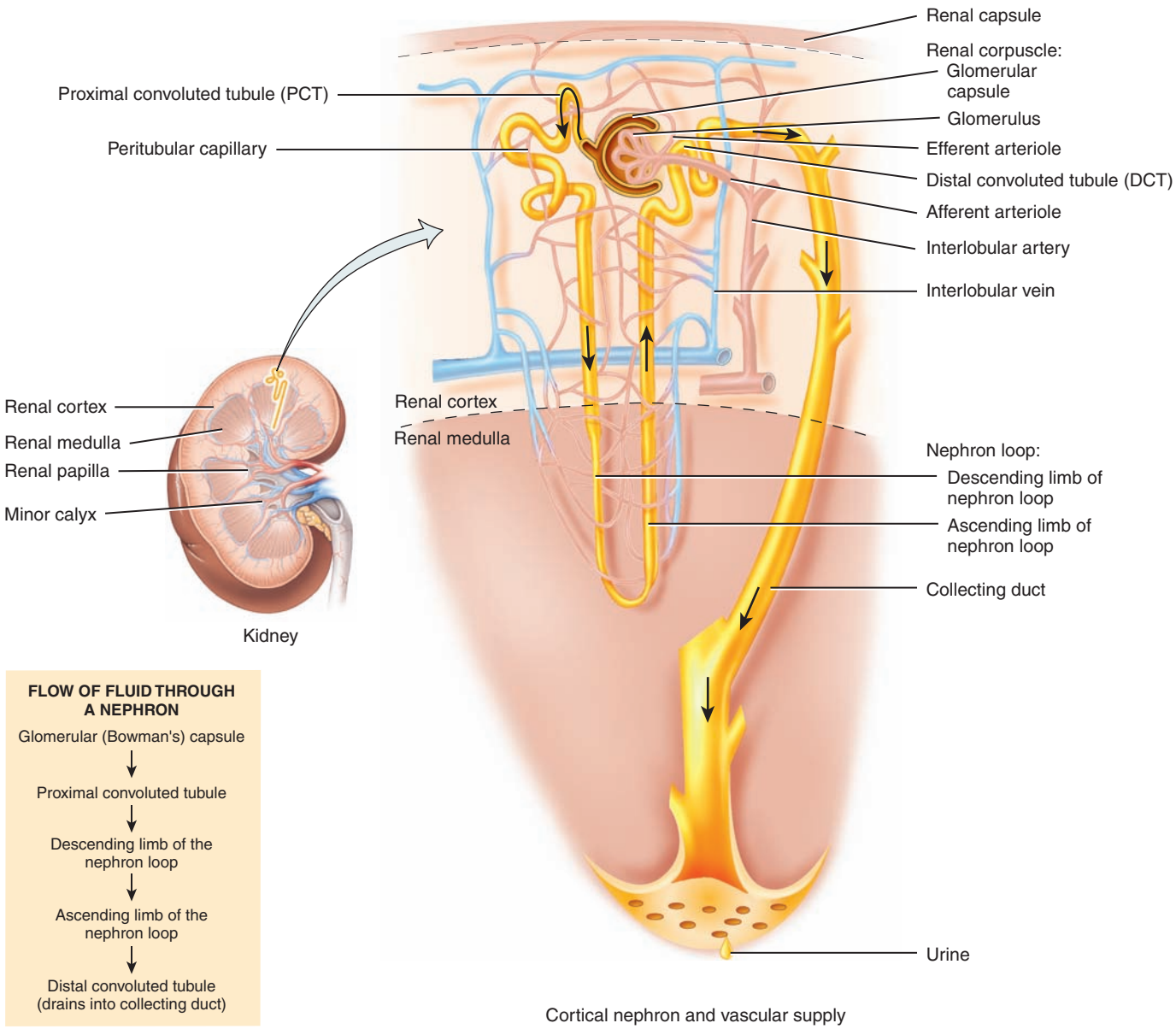
The tubule that extends from the glomerular capsule is the proximal convoluted tubule. *Proximal* means "close to," and *convoluted* means "having twists or coils." This part of the tubule does have plenty of twists and turns. From the PCT, the newly filtered fluid is transported into the loop of the nephron (named the loop of Henle). This portion of the nephron extends from the cortex into the medulla of the kidneys, making up a portion of the renal pyramid. The loop dives down into the medulla and back up to the cortex, where it joins with the distal convoluted tubule (DCT). *Distal* means "further from," indicating that this coiled tubule lies some distance from the glomerulus. The DCT leads directly to the collecting duct.

One collecting duct gathers newly formed urine from a series of nephrons and drains it to the renal pelvis. These collecting ducts comprise the majority of the renal pyramids. The urine that reaches the renal pelvis is almost ready for excretion from the body. As it travels through the rest of the urinary system, it is subjected to small adjustments in composition before it is voided, or released.

Amazingly, the body maintains more nephrons than it needs. This situation is not characteristic of the human body—usually when there is an excess of proteins, compounds, or structures, the body will break down the excess and retain only the bare minimum needed for

Nephron with capillary bed • Figure 16.3

The nephron is the filtering unit of the urinary system. It is here that the homeostatic fluid balance of the entire system is carried out.



survival. Recall that unused muscular tissue atrophies, leaving no sign of its existence. Literally millions of extra nephrons are maintained. We have enough filtering capacity in one kidney to provide all the cleansing and monitoring of fluid balance necessary for life. Having two kidneys allows us to donate a kidney for transplant and not suffer adverse effects on either fluid balance or general well-being.

CONCEPT CHECK

STOP

1. **What** are the functions of the urinary system?
2. **What** are the organs of the urinary system? **Which** is the organ that filters the bood?
3. **What** is the hilus? Renal pyramids? The renal pelvis? Nephrons?

16.2 Urine Is Made, Transported, and Stored

LEARNING OBJECTIVES

1. **Define** glomerular filtration.
2. **Explain** the functions of the PCT, loop of the nephron, and DCT.
3. **Outline** the functions of the bladder and the urethra.

Urine formation begins in the glomerulus and is finalized in the renal pelvis, through the processes of filtration, active transport, and osmosis. As blood passes through the glomerulus of the nephron, most of the liquid is forced out of the arteriole and into the lumen of the nephron. This first step of urine formation is termed **glomerular filtration**. Water, nitrogenous wastes, nutrients, and salts are all forced from the blood at this point.

Glomerular Filtration Is the First Step in Urine Formation

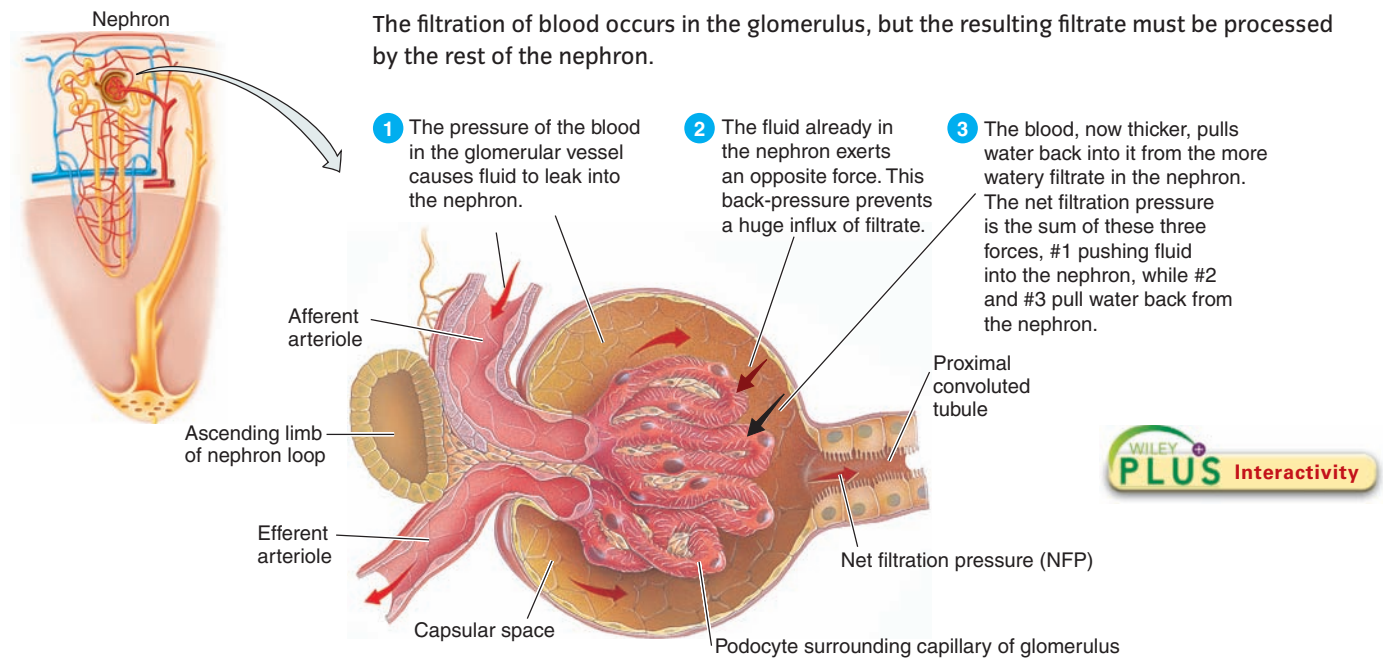
To understand how this filtration occurs, it may help to review the material on osmosis and pressure in Chapter 4. Glomerular blood pressure is higher than systolic blood pressure. This increase is partially caused by the kinking and twisting of the glomerular vessels. You have experienced this in a garden hose if you have ever bent it. The pressure increases because the water must travel past the obstructions. A similar phenomenon occurs in the glomerular vessels. In addition, the incoming (afferent) arterioles have a larger diameter than the outgoing (efferent) glomerular arterioles. This difference increases pressure in the glomerulus by creating back-pressure. The total pressure on the blood forces most of the fluid into the capsule. To filter the blood, the blood pressure must overcome the pressure of the fluid already in the capsule (capsular pressure), as well as the osmotic pressure of the blood itself.

Because the glomerular system relies on pressure, there is a lower limit to its functioning. See **Figure 16.4**. If your systolic pressure drops below 60 mmHg, blood in the glomerulus will not be forced through the glomerular wall because glomerular pressure will not rise high enough to force plasma from the blood vessels. Serious complications can result, because the aqueous portion of

PROCESS DIAGRAM

THE PLANNER

Glomerular filtration • Figure 16.4



Renal corpuscle (internal view)

I WONDER...

Is "Smart Water" Really a Smart Choice?

For years now, coaches have been telling athletes to drink water with added sugars and salts in order to prevent cramping and fatigue. As more adults participate in sports, beverage companies have begun to mass-produce sports drinks, marketing them in convenience stores and food stores. Are these more expensive, calorie-laden sports drinks really better than water? When we work out, we lose water and electrolytes through our sweat. The electrolytes we lose include sodium, potassium, calcium, and magnesium, as well as traces of zinc, iron, chromium, nickel, and lead. After strenuous activity, we feel dehydrated, with muscles that are fatigued and weak. Amazingly, some people lose up to three pounds of fluid an hour while exercising. This fluid must be replaced. In order to replace this, our thirst center triggers us to reach for a drink. Water will replace the volume lost, but will not add any electrolytes. Sports drinks that include sodium, potassium, and carbohydrates may in fact replenish our fluids more quickly. The salt in them will maintain that thirsty feeling, causing you to drink more than if you were drinking plain water. Also, the carbohydrates seem to maintain muscle strength more effectively than water alone. Dr. Larry Kenney, professor of physiology and kinesiology at Penn State University, suggests that sports drinks are a better choice if you have participated in athletics for over 45 minutes. "The longer the activity, the more important sports drinks become."

the blood cannot filter into the nephron and therefore cannot be cleansed. Three criteria must be met in order to filter blood plasma through the glomerulus:

1. Blood pressure must be high enough to force plasma out of the glomerular vessel walls.
2. The fluid already in the glomerulus must have a low enough pressure to allow more fluid to be forced into the nephron tubules.
3. The osmotic pressure of blood in the peritubular capillaries must be high enough to draw water back into the capillaries from the nephron tubule.

If these three conditions are not met, the nephron cannot filter the blood, and the urinary system will fail.

During filtration, the formed elements and plasma proteins remain in the glomerular vessel because they are too large to pass through the cells that line the glomerulus. The proteins left in the capillary blood are essential because they set up the osmotic gradient that later pulls most of the water from the filtrate back into the blood. Every day, approximately 180 liters of fluid are filtered from the blood, but only a small fraction of that is excreted. Imagine how different life would be if we lost 180 liters of fluid every day! That is equal to 60 times the total plasma volume of the body. Not only would we have to drink constantly, but we would most likely also have a different social custom surrounding the need to urinate, because it would occur almost constantly. In the body as in the biosphere, recycling makes a real difference.

We do have to replace the volume of fluid we excrete, to maintain blood volume and keep our bodies hydrated. One of the ways we replace that fluid is to drink water, as seen in *I Wonder… Is "Smart Water" Really a Smart Choice?*

Tubular Reabsorption Recycles Water to the Blood

As filtrate passes through the nephron, ions and water are returned to the peritubular capillaries in a process called **tubular reabsorption**, the second step in urine formation. Approximately 80% of the filtered water is returned to the blood immediately at the PCT. Glucose, amino acids, and salts are also returned to the bloodstream. The walls of the proximal convoluted tubule have a large surface area to accommodate

microvilli Small hair-like folds of the cell membrane that increase the cell's surface area for absorption.

facilitated diffusion Movement of substances across a membrane from high concentration to low with the assistance of a carrier molecule.

all this reabsorption. The cells that line the PCT are covered with **microvilli**. These cells are adjacent to the endothelial cells of the peritubular capillaries, creating a thin layer that allows diffusion from the tubule to the blood.

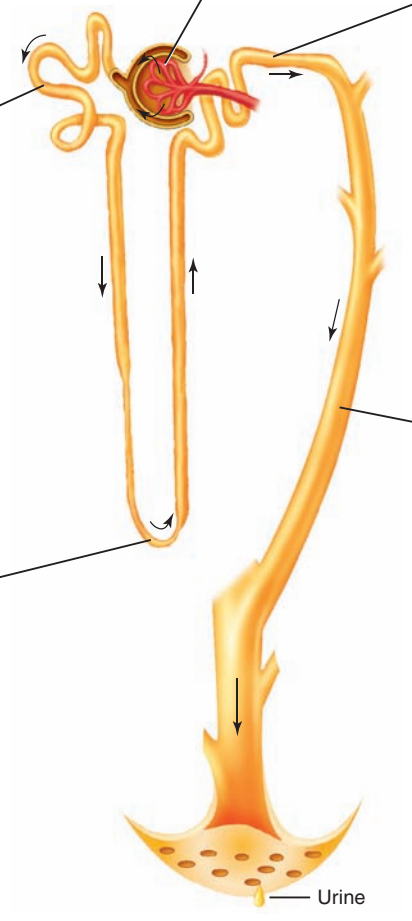
Essential ions and water are sent back to the blood via osmosis and diffusion (**Figure 16.5**). Glucose returns using **facilitated diffusion**. The walls of the PCT have a finite number of glucose receptors to pick up glucose from the filtrate. Normally, there are enough receptors to remove all the glucose from the filtrate and return it to the blood. However, excess glucose in the blood will overrun these receptors and drop from the PCT into the loop of the nephron. Once beyond the PCT, glucose cannot be returned to the bloodstream. It is said to "spill" into the urine because it literally spills into the loop. One symptom of diabetes mellitus is glucose spilling as a result of very high levels of glucose in the original filtrate.

Tubular Secretion Removes Products from the Blood

Waste products and other unwanted substances too large to filter from the blood at the glomerulus, such as steroids

Urine formation • Figure 16.5

Urine formation begins in the glomerulus, where blood plasma is filtered and collected. At the PCT, most of the water and many ions and nutrients are reabsorbed by the blood. The loop removes more water and ions. The distal convoluted tubule allows for final adjustments in the composition of urine and blood by actively secreting larger substances from the blood to the urine.



GLOMERULUS

Glomerular filtration rate: 105–125 mL/min

Filtered substances: water and all solutes present in blood (except proteins) including ions, glucose, amino acids, creatinine

PROXIMAL CONVOLUTED TUBULE

Reabsorption (into blood) of filtered:

Water	65% (osmosis)
Glucose	100%
Amino acids	100%
Na^+	65%
K^+	65%
Cl^-	50%
HCO_3^-	80–90%
Ca^{2+}, Mg^{2+}	variable
Urea	50%

Secretion (into urine) of:

H^+	variable
Ammonia	variable
Urea	variable
Creatinine	small amount

NEPHRON LOOP

Reabsorption (into blood) of:

Water	15% (osmosis in descending limb)
Na^+	20–30% (ascending limb)
K^+	20–30% (ascending limb)
Cl^-	35% (ascending limb)
HCO_3^-	10–20%
Ca^{2+}, Mg^{2+}	variable

Secretion (into urine) of:

Urea	variable

DISTAL CONVOLUTED TUBULE

Reabsorption (into blood) of:

Water	10–15% (osmosis) 5–9% (insertion of water channels stimulated by ADH)
Na^+	6–9%
HCO_3^-	variable amount
Cl^-	5%
Ca^{2+}	variable
Urea	variable

Secretion (into urine) of:

Steroids Drug breakdown products Histamine Creatinine Potassium	amounts are variable based on physiology

COLLECTING DUCT

Secretion (into urine) of:

K^+	variable amount to adjust for dietary intake (leakage channels)
H^+	variable amounts to maintain acid–base homeostasis (H^+ pumps)

Tubular fluid leaving the collecting duct is dilute when ADH level is low and concentrated when ADH level is high.

secreted In this sense, actively transported from the blood to the filtrate.

and drug breakdown products, are actively **secreted** into the filtrate at the distal convoluted tubule. Tubular secretion is then the third step in urine formation. Tubular secretion provides a final fine-tuning of the dissolved compounds in the blood. This process occurs at the DCT and also provides clues as to the amount and type of drugs that are traveling through the body. Most of the breakdown products of drugs, both pharmaceutical and recreational, are large and must be secreted, or actively pushed into the nephron.

The loop of the nephron and the collecting duct remove even more water from the filtrate, serving to precisely regulate fluid loss. Interestingly, the descending arm of the loop of the nephron is permeable to water, but the ascending limb is not. Therefore, water leaves the filtrate as it moves down the loop of the nephron, and salts leave the filtrate as it flows up the ascending arm, creating a salt gradient in the medulla of the kidney.

Urine Is Transported to the Bladder for Storage

Once the filtrate has passed through the nephron and collecting ducts and reaches the renal pelvis, it is finally referred to as urine. Most of the fine-tuning of ion concentration and water content is completed by this point (see **Table 16.1**). Water can still be removed as the urine sits in the remaining organs of the urinary system, but the salt content is relatively stable.

Kidney stone • Figure 16.6

A typical small kidney stone is seen here on the tip of a finger. Stones can be as large as a pearl or even, rarely, a golf ball.

While in the renal pelvis, water can continue to leave the urine, concentrating the salts in the urine, which can lead to the formation of kidney stones. These rock-like masses, usually composed of **calcium oxalate**, can grow large enough to block renal flow—see **Figure 16.6**. Kidney stones are extremely painful as they move through the urinary pelvis and

calcium oxalate A chemical compound composed of calcium ions bound to the oxalate ion ($C_2O_4^{2-}$).

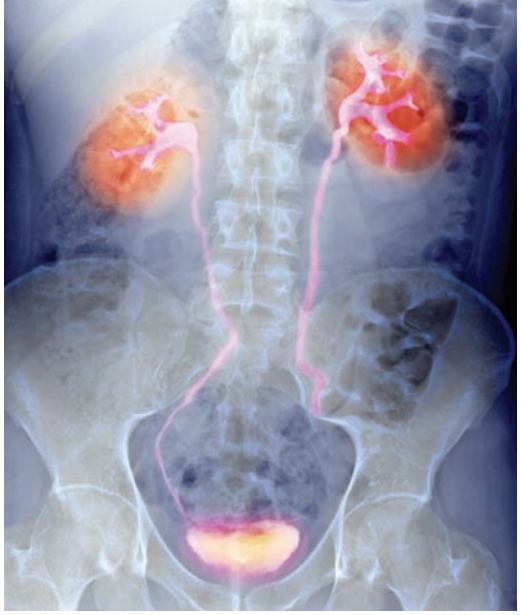
Substances filtered, reabsorbed, and excreted in urine per day Table 16.1

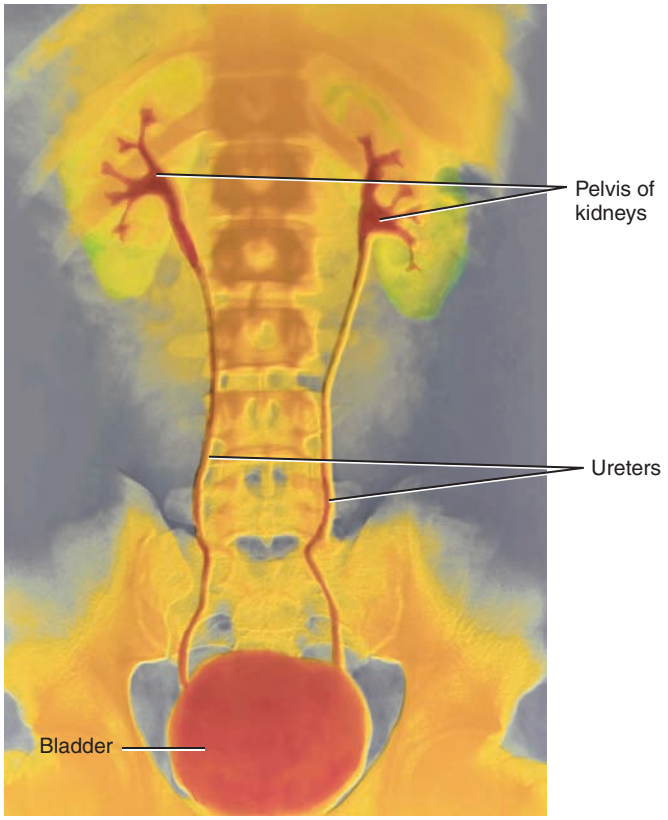
Substance	Filtered* (enters renal tubule)	Reabsorbed (returned to blood)	Excreted in urine
Water	180 L	178–179 L	1–2 L
Chloride ions (Cl^-)	640 g	633.7 g	6.3 g
Sodium ions (Na^+)	579 g	575 g	4 g
Bicarbonate ions (HCO_3^-)	275 g	274.97 g	0–0.03 g
Glucose	162 g	162 g	0
Urea	54 g	24 g	30 g†
Potassium ions (K^+)	29.6 g	29.6 g	2.0 g‡

*Assuming that glomerular filtration is 180 L per day.

†In addition to being filtered and reabsorbed, urea is secreted.

‡After virtually all filtered K^+ is reabsorbed in the convoluted tubules and loop of Henle, a variable amount of K^+ is secreted in the collecting duct.





Ureters and bladder • Figure 16.7

Ureters carry urine from the renal pelvis to the urinary bladder. They are approximately 20 centimeters long and curl behind the urinary bladder to enter from the trigone, or base of the bladder. These tubes are ringed with smooth muscle, which helps propel the urine to the bladder. The walls of the bladder, a distensible organ, are lined with transitional epithelium. These cells also secrete mucus to protect the bladder from toxic compounds in the urine.

can become lodged in the kidney or the ureters. Some kidney stones are jagged or pointy, making them even more likely to jam. Removal of kidney stones rarely requires medical assistance. Drinking lots of water and resting as the stone moves through the renal pelvis and ureter often do the trick, but some stones are too large to pass. These may be broken apart by ultrasound waves so the fragments can be excreted. Because kidney stones often reappear, patients are advised to avoid foods high in calcium, eat less protein (to decrease urine acidity), and drink more fluids, especially water.

Urine travels down the ureters. From the renal pelvis, urine travels down the ureters, as seen in **Figure 16.7**, to the urinary bladder. The ureters are long, thin muscular tubes lined with mucosa. The ureters loop behind the urinary bladder and enter it at the base. This positioning allows the bladder to expand upward without dislodging the ureters.

With every heartbeat, blood is pushed into the glomerulus and filtered. The nephrons constantly form urine, so the tubes and ducts of the urinary system are always full of fluid. As more urine is produced, it pushes what is already formed down the ureters and into the bladder, where small contractions move the urine toward the bladder.

The urinary bladder stores urine before release. The urinary bladder is a hollow, variable-sized organ, as shown in Figure 16.7. It lies in the pelvic cavity, posterior to the pubic bones and the pubic symphysis. The base of the bladder has a triangular area where the two ureters enter and the urethra exits. This area is called the trigone. The bladder is lined with transitional epithelium to allow for expansion without tearing or destroying the integrity of the inner lining. The empty bladder is the size of a walnut, but it can stretch to hold up to 800 ml of fluid in males and slightly less in females.

Discharging urine from the bladder is called urinating, voiding, or micturition. This reflex involves both smooth and skeletal muscles. Urine is constantly forming and draining into the bladder. When the bladder contains approximately 300 ml, pressure in the bladder stimulates stretch receptors that send nerve impulses to the micturition center in the central nervous system. The micturition reflex causes contraction of the walls of the bladder and relaxation of the **internal urethral sphincter** muscle. Urine moves down into the urethra, pressing on the **external sphincter muscle**. At this point, you can consciously control the opening of the external urinary sphincter. Should you choose not

internal urethral sphincter Ring of involuntary smooth muscle that keeps the urethra closed.

external sphincter muscle Ring of voluntary skeletal muscle that closes the urethra.

to empty the bladder, the urge to urinate will subside until the next 300 ml collects in the bladder.

As we mature, we learn to anticipate and control this reflex, but we cannot delay micturition indefinitely. The bladder continues to expand, and a second reflex will begin shortly. Just as we are not able to hold our breath until we die, we cannot retain urine until the bladder bursts. When the bladder reaches 700 to 800 ml, micturition occurs despite our best efforts to control the external urethral sphincter.

The Urethra Transports Urine out of the Body

When micturition occurs, the urine leaves the body via the urethra, a single tube extending from the trigone of the bladder to the exterior. In females, the urethra is a short 5 cm, emptying in front of the vaginal opening. The male urethra is almost four times longer because it runs the length of the penis, as seen in **Figure 16.8**. The urinary and reproductive systems join in the male, sharing the male urethra. In the female, the two systems are separate. The female urethra carries only urine, and the female reproductive tract opens at the vagina.

Because the female urethra is so much shorter, women suffer far more urinary tract infections (UTIs) than men. Bacteria outside the body can travel the short distance up the urethra and colonize the bladder, resulting in painful urination, often accompanied by bleeding from the irritated bladder walls. (If the urine contains glucose, the bacteria multiply even faster.) UTIs are serious infections that must be cleared up, usually by taking antibiotics. If the bacteria remain in the bladder, they will eventually travel up the ureters and colonize the pelvis and tubules of the kidney. Kidney infections are painful and serious because they block normal kidney function and can lead to kidney failure.

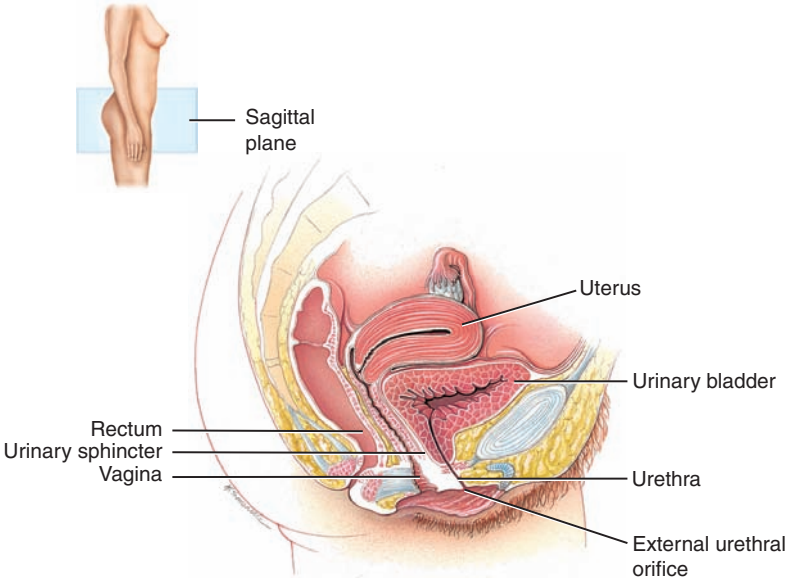
Incontinence Is the Loss of Control over Voiding

As we age, many things change, including our ability to control micturition when the urge arises. **Incontinence** can and does occur in all age brackets, genders, and social levels, but it is far more common in elderly women. Perhaps the stress of bearing children weakens the muscles of the pelvic floor, leading to greater difficulty controlling these muscles in later years.

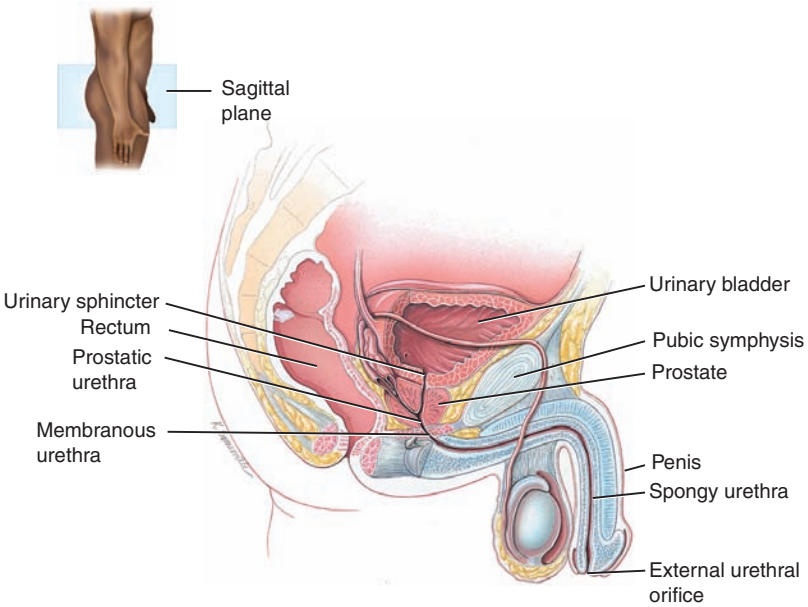
incontinence The inability to prevent urine leakage.

An estimated 12 million Americans suffer incontinence, and most do not require surgery. Incontinence can be a symptom of many different pathologies, but it is not a pathology in its own right. Causes include chronic

Comparison of female and male urethras • Figure 16.8



a. Sagittal section showing the female urethra



b. Sagittal section showing the male urethra

urinary tract infections, side effects of medication, muscular weakness, an enlarged prostate gland in males, **constipation**, or neuromuscular disease. There are three types of incontinence determined by the underlying cause of the problem, each with the same result:

constipation Difficult or infrequent defecation, leading to dry, potentially painful fecal evacuation.

- **Stress incontinence** is the leaking of urine during physical exertion.
- **Urge incontinence** is the inability to quell the urge to urinate.
- **Overflow incontinence** is the overflowing of the urinary bladder caused by waiting too long before urinating, as happens in young children who are learning to control their sphincter muscles.

Treatment for incontinence is tailored to the cause. Muscular strengthening exercises or behavioral modification may be recommended.

CONCEPT CHECK STOP

1. **What** is glomerular filtration?
2. **Which** portion of the nephron is involved in secretion? In reabsorption? In water balance?
3. **What** are the main functions of the bladder and urethra?

16.3 The Urinary System Maintains the Body's Fluid and Solute Balance

LEARNING OBJECTIVES

1. **Explain** the function of ADH, aldosterone, ANP, and BNP.
2. **Explain** the role of the kidneys in maintaining blood pH.
3. **Define** the bicarbonate buffering system of the blood.

A key function of the kidneys is to maintain the body's water and salt balance. We excrete or reabsorb many substances in an effort to keep our blood volume relatively constant and our blood pH at roughly 7.4. It is worth noting that the urinary system returns key nutrients—carbohydrates, lipids, and proteins—to the body. It is NOT a function of the urinary system to regulate these nutrients.

The Urinary System Maintains the Body's Water–Salt Balance

osmolarity Osmotic pressure of a solution.

Excreted urine usually has a much different **osmolarity** than the blood. When originally filtered from the blood, the fluid in the nephrons has the same water-to-solute ratio as the blood. As it moves through the nephron, this ratio changes to produce concentrated or dilute urine, depending on the body's demands. Dilute urine is produced by removing **solutes** from the forming urine leaving the nephron. Water does not routinely pass back to the bloodstream across the walls of the DCT or the collecting tubule. As the ion concentration drops in the urine, the water proportion increases, so fluid reaching the collecting duct is far less concentrated than blood plasma, resulting in dilute urine.

solute Substance dissolved in a solvent.

Concentrated urine is produced by the reabsorption of water at the loop of the nephron and the collecting duct. The cells of the DCT can be controlled to reabsorb water by the presence of certain hormones. Water can also be reabsorbed across the walls of the urinary bladder. This reabsorption explains why the first morning urination is more concentrated than urine produced and passed later in the day.

Water can be reabsorbed into the bloodstream at the DCT and collecting duct with help from the hormone ADH (antidiuretic hormone). A diuretic increases the volume of urine produced, whereas an antidiuretic has the opposite effect.

ADH will therefore decrease urine volume. ADH is secreted by the posterior lobe of the pituitary gland, located on the undersurface of the brain, in response to blood volume. ADH in the blood causes the cells surrounding the collecting duct and the DCT to remove more water from the urine, returning it to the depleted bloodstream. See **Figure 16.9**.

Surprisingly, sodium is conserved almost as stingily as water. It is important to remember that where sodium goes, water follows. If you live in a humid area, you already know this. In the Deep South, the Midwest in summer, the southern shorelines of the East and West Coasts, and on Pacific islands, humidity can clog saltshakers because sodium chloride draws water molecules from the air, causing clumps in the saltshaker. If you add a few grains of uncooked rice to the saltshaker, they will absorb the water from the salt and prevent the salt crystals from sticking together.

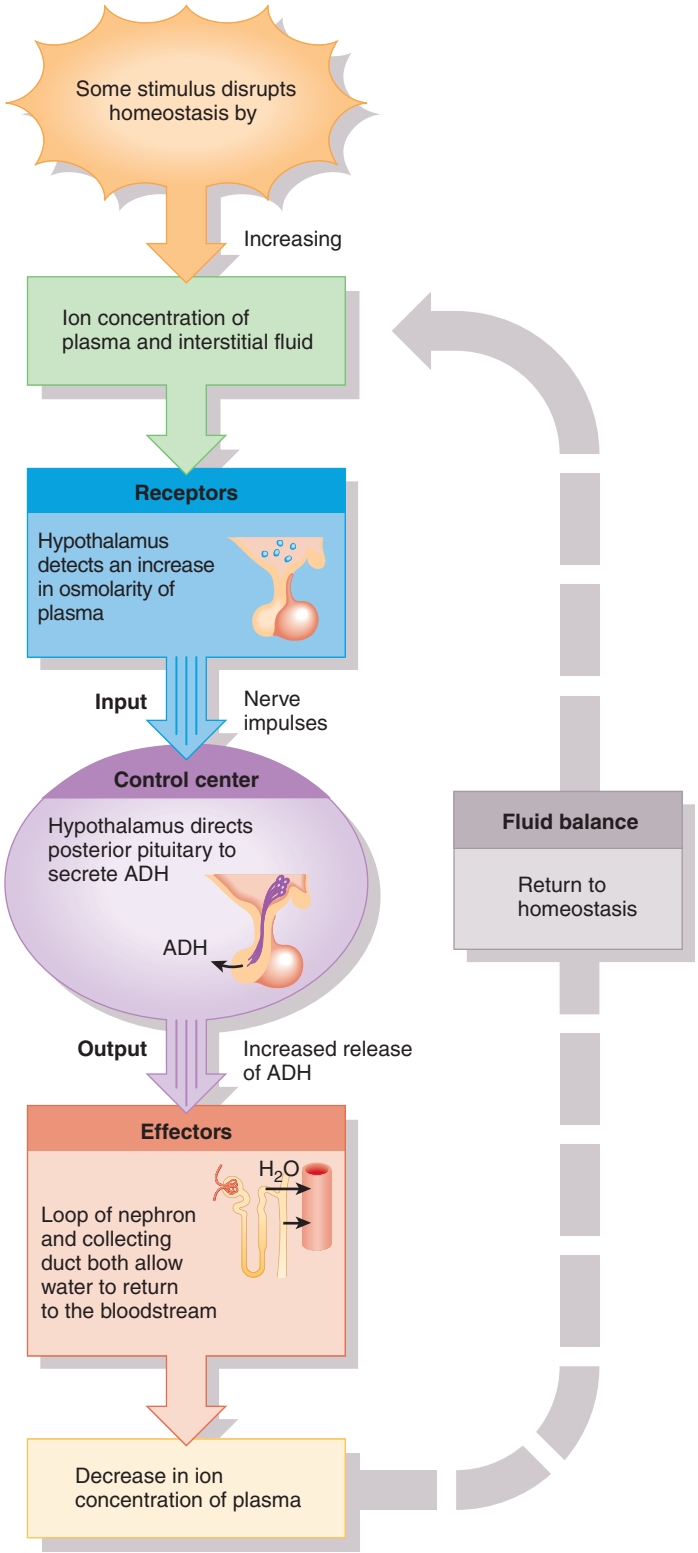
In the nephron, this attraction between water and sodium is used to good advantage. More than 99% of the sodium filtered from the blood at the glomerulus is returned before the urine leaves the nephron. Two-thirds of this reabsorption occurs at the PCT. Another 25% of the filtered sodium is removed from the forming urine at the ascending limb of the loop of the nephron. This loop sets up a sodium gradient in the medulla of the kidney by removing sodium from the filtrate. Sodium is also reabsorbed from the DCT and the collecting duct, so sodium levels are strictly maintained. For more on salt consumption, see *What a Scientist Sees: Why Is Salt Intake Important?* on the following page.

Several hormones and chemicals affect salt regulation. The hormones aldosterone, atrial natriuretic peptide (ANP), and brain natriuretic peptide (BNP) all regulate sodium reabsorption at the distal convoluted tubule. Aldosterone causes the excretion of potassium ions into the filtrate and the reabsorption of sodium ions from the forming urine, so water will leave the filtrate with the sodium ions and remain in the tissues of the body. ANP and BNP both increase blood volume and blood pressure.

Ingested chemicals can also affect nephron function. Caffeine and alcohol both increase urine production, apparently through decreased ADH production. When caffeine is ingested in quantities below 350 mg, we experience central nervous system stimulation, decreased sleepiness, and possible increases in athletic performance.

ADH feedback system • Figure 16.9

If you drink less water than you need, ADH will be secreted to preserve the volume of water in your body. A small volume of more concentrated urine will be produced. Conversely, if you drink a lot of water, ADH will not be secreted, and more fluid will be lost through the urinary system.



WHAT A SCIENTIST SEES

Why Is Salt Intake Important?

Table salt is sodium chloride, and sodium is about as essential as electrolytes get because it helps control osmosis throughout the body. However, eating a lot of salt can raise blood pressure by causing a subtle swelling of the tissues. Sodium is so critical to our survival, however, that we also have a lower limit below which our bodies again shut down. Hyponatremia (low sodium levels) is also called water intoxication and can lead to death if not treated properly.

The two images seen here, **a** and **b**, indicate opposing sodium balance issues. When a person appears swollen and puffy, as in **Figure a**, we usually think they have a weight issue. A scientist however, immediately sees an excess of sodium in the diet. That excess sodium is causing water retention in tissues, resulting in the puffy appearance of the individual. Alternatively, when watching extreme endurance sports (those lasting longer than 4 hours), we may see a competitor completely fall apart, as in **Figure b**. Our response is that the person either did not train properly for the event or "went out too hard," using all her reserves before she reached the finish line. In fact, what may have happened is that the athlete over-hydrated during the event, diluting the blood sodium while at the same time losing sodium to sweat, and is suffering from hyponatremia. In this instance, excessive sweating has removed precious reserves of sodium, which are not replaced with the intake of plain water. Immediate rest along with intake of ion-enriched fluids is essential to restore normal functioning.

In 2004, the National Academy of Sciences waded into the salt debate by suggesting that people ages 19 to 50 ingest at least 1.5 g of sodium (3.75 g of salt) per day. This intake, the group's experts said, would replace losses due to sweating and help ensure an adequate supply of other nutrients. The National Academy also recommended a maximum of 2.3 g of sodium (5.75 g salt) and mentioned the danger of hypertension associated with increased levels. For many people who eat processed food, keeping under that maximum poses a problem.

NATIONAL GEOGRAPHIC

Think Critically

1. What clues might you use to correctly diagnose excess sodium in the tissues rather than normal weight gain? Do you think sodium water retention would occur more or less quickly than the usual weight gain due to excess caloric intake?
2. Is your daily sodium intake adequate? Do you participate in activities that might alter your maximum sodium requirements? Does your place of residence (the Midwest versus the Deep South, for example) affect your need for sodium?

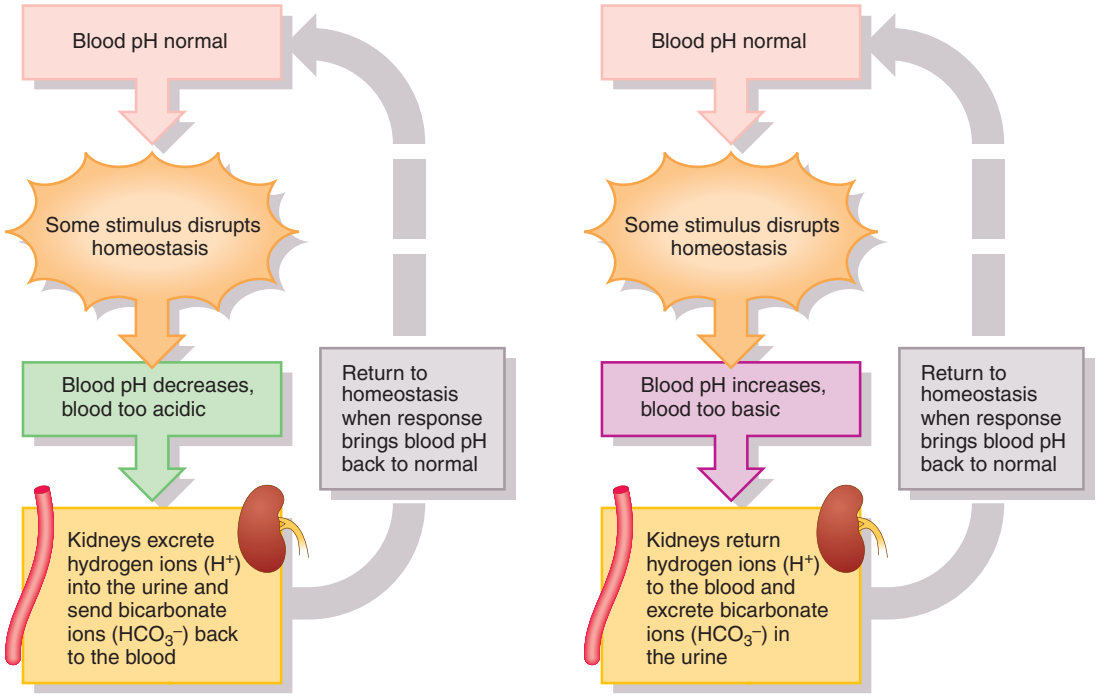
However, the side effects include headache and drowsiness as the caffeine wears off and also insomnia. The diuretic effects of caffeine are not particularly helpful during athletic endeavors either. Dehydrated muscles cramp more easily and are less likely to be repaired after injury. Your body cannot achieve peak function without good hydration.

The Kidneys Help Maintain the Blood's Acid–Base Balance

Body pH must be held within a narrow range (7.35 to 7.45). This is done primarily through the bicarbonate buffer system of the respiratory system, with help from the urinary system. This pH stability is achieved through chemical equilibrium. In the body, all three of the product sets shown below are in

Urinary system regulation of blood pH • Figure 16.10

When blood becomes too acidic, or too basic, the kidneys respond as shown. Urine is usually acidic, meaning that the excess of hydrogen ions typically found in the blood is filtered into the urine. Normally, there is not an excess of bicarbonate ions in the blood to filter into the urine; however, urine pH fluctuates according to the physical state of the body and is considered normal between pH 4.6 and 8.0. High-protein diets can increase acidity, whereas vegetarian diets increase alkalinity.



equilibrium, balanced as if on a teeter-totter. Adding water to the body increases the reactants at the right ($H_2O + CO_2$), causing the amount of H_2CO_3 and $H^+ + HCO_3^-$ to increase proportionately as the reactions return to equilibrium. This is called "pushing the reaction to the left."

$$H^+ + HCO_3^- \leftrightarrow H_2CO_3 \leftrightarrow H_2O + CO_2$$

When carbon dioxide is exhaled, the above reactions are "pushed to the right." In order to maintain an equal concentration of reactants on either side of the arrows, more hydrogen ions are picked up by the bicarbonate ion and removed from the blood, returning the reaction to a point where all three compartments are equal. This homeostatic function is so vital that the rate and depth of breathing respond to the level of carbon dioxide in the blood, not to the level of oxygen. When blood pH decreases (due to increased H^+ concentration), the breathing rate increases. When blood pH rises, breathing is depressed, providing an instantaneous "fix" for blood pH.

Although the respiratory system is the main regulator of blood pH, the kidneys also play a role, as seen in

Figure 16.10. Whereas the bicarbonate system uses an equilibrium reaction, the urinary system removes acidic and basic substances from the fluid and literally flushes them out. If the blood is too acidic, the kidneys can excrete hydrogen ions and send bicarbonate ions back to the blood. Conversely, if the blood is too basic, the kidneys will return hydrogen ions to the blood and excrete bicarbonate ions. This process may adjust pH more slowly than the respiratory system does, but the results are permanent.

CONCEPT CHECK

STOP

1. **What** two hormones prevent water loss at the kidneys? **What** is the function of ANP and BNP?
2. **How** does the urinary system help maintain fluid pH in the body?
3. **How** does the bicarbonate buffering system of the blood work?

16.4 Life-Threatening Diseases Affect the Urinary System

LEARNING OBJECTIVES

1. **List** the health facts that can be learned from routine urinalysis.
2. **Explain** the processes of conventional dialysis and hemodialysis.

Chemical analysis of urine can reveal a number of serious diseases as well as the use of illegal drugs (see *Ethics and Issues: How Does a Urine Test Prove Drug Abuse?*). Urinalysis (UA) is a simple, common test routinely done in the doctor's office. It is noninvasive, meaning that instruments or sensing equipment are not placed in or on your body. Because urine is the by-product of filtered blood, any unusual compounds or incorrect levels of normal blood constituents will appear in the urine.

Warning Signals from Urinalysis

Abnormal components in urine can include albumin, hemoglobin, red blood cells, white blood cells, glucose, and **casts**. Each can indicate a specific problem. See Table 16.2 on this page for listings of the normal and abnormal constituents of urine and Table 16.3 on page 448 for the abnormal ones.

casts Small structures formed by mineral or fat deposits on the walls of the renal tubules.

- **Albumin** is a small protein that, if present in the urine, must be entering at the glomerulus. This could reflect excessively high blood pressure in the glomerulus that forces proteins through the podocyte walls, or tears in glomerular arterioles. Normally, albumin remains in the blood to provide blood osmotic pressure. Proteins in the urine are diagnosed as proteinuria, but this may not indicate pathology. Serious weight training puts tremendous pressure on the capillaries and can force protein into the urine.
- **Hemoglobin** indicates bleeding in the upper urinary tract. Intact red blood cells would indicate bleeding closer to the lower end of the urinary tract, perhaps in the urethra. **White blood cells** in the urine indicate that an immune response is occurring, usually in response to an infection of the urinary tract or occasionally the kidney.
- **Glucose** in the urine signifies diabetes mellitus. As described previously, glucose spills into the urine due to a high concentration in the blood.
- **Casts** are plugs of material, shaped like the nephron, that build up in the tubules and then get forced out by pressure. Casts can be formed from minerals that enter with the filtrate, or they can be composed of proteins and cells that find their way into the system. Casts always indicate serious kidney trouble.

Normal constituents of urine Table 16.2

Normal constituent	Description
Volume	One to two liters in 24 hours but varies considerably.
Color	Yellow or amber but varies with urine concentration and diet. Color is due to urochrome (pigment produced from breakdown of bile) and urobilin (from breakdown of hemoglobin). Concentrated urine is darker in color. Diet (slightly red urine from beets), medications, and certain diseases affect color. Kidney stones may produce blood in urine.
Turbidity	Transparent when freshly voided but becomes turbid (cloudy) upon standing.
Odor	Mildly aromatic but becomes ammonia-like upon standing. Some people inherit the ability to form methylmercaptan from digested asparagus that gives urine a characteristic odor. Urine of diabetics has a fruity odor due to presence of ketone bodies.
pH	Ranges between 4.6 and 8.0; average 6.0; varies considerably with diet. High-protein diets increase acidity; vegetarian diets increase alkalinity.
Specific gravity	**Specific gravity** is the ratio of the density of a substance to the density of pure water. In urine, it ranges from 1.001 to 1.035. The higher the concentration of solutes, the higher the specific gravity.

ETHICS AND ISSUES

THE PLANNER

How Does a Urine Test Prove Drug Abuse?

Urinalysis (UA) is a noninvasive way to understand the events occurring in the body. If a person has been taking illicit drugs, prescribed medications, or even diet supplements, indications of those compounds will show up in the urine.

Urinalysis is most often used as a diagnostic tool when people complain of abdominal pain, back pain, painful or frequent urination, blood in the urine, or symptoms of a urinary tract infection. It is also a routine part of regular physical examinations.

An abnormal UA can be an early warning of trouble, because substances like protein or glucose begin to appear in the urine before a person is aware of a problem. The healthcare provider must correlate the urinalysis results with physical complaints to make a diagnosis.

In a typical urinalysis, the specimen is first examined for its physical characteristics. The next step is a chemical analysis, usually with a "dipstick" test that includes many pads soaked with indicator substances. After wetting the pads, the color of each is compared to a reference chart.

Urine usually contains urochrome, which gives it that yellow color; nitrogenous wastes like ammonia and urea from metabolic processes; water; ions; and cast-off cells from the epithelial linings of the system. In addition, large molecules enter the urine when blood passes the distal convoluted tubule. These molecules can include breakdown products of legal and illegal drugs, vitamin and mineral supplements, or even various environmental contaminants.

When urinalysis is used to test for the presence of drugs, the sample is first put through a fast and inexact screening test. Samples that test positive are then put into an analytical machine called the gas chromatograph-mass spectrometer (GC/MS). The machine is expensive but is so sensitive that it can easily detect traces of compounds at concentrations of one part per billion or less. If peaks on the graph indicate the presence of illicit drugs or their metabolites, the test is said to be positive, and the person is considered a user of illicit drugs.

Critical Reasoning Issues Drug testing is often sold as a cure-all for detecting drug use, but urinalysis is not perfect. A test result can mistake metabolites of over-the-counter or prescription drugs for those of illicit drugs, forcing test administrators to interpret results carefully. Marijuana and other drugs are detectable in the urine for long periods, whereas alcohol and cocaine are cleared quickly from the body. Finally, drug testing is expensive, and some studies suggest that the knowledge that urinalysis will be performed on a regular basis has little effect on employee performance.

Think Critically

1. Given the above limitations, what kind of privacy safeguards should employers and others testing for drugs build into their testing process?
2. The most common "street" advice for passing as "clean" despite having recently taken illicit drugs is to dilute the urine by drinking massive quantities of water. Deliberately ingesting compounds that will interfere with drug tests raises many ethical questions. Should these "interferences" be interpreted as a sign that the person being tested is using illegal drugs?

Abnormal constituents of urine Table 16.3

Abnormal constituent	Description
Albumin	A normal constituent of plasma, it usually appears in only very small amounts in urine because it is too large to pass through capillary fenestrations. The presence of excessive albumin in the urine—**albuminuria**—indicates an increase in the permeability of filtration membranes due to injury or disease, increased blood pressure, or irritation of kidney cells by substances, such as bacterial toxins, ether, or heavy metals.
Glucose	The presence of glucose in the urine is called **glucosuria** and usually indicates diabetes mellitus. Occasionally it may be caused by stress, which can cause excessive amounts of epinephrine to be secreted. Epinephrine stimulates the breakdown of glycogen and liberation of glucose from the liver.
Red blood cells (erythrocytes)	The presence of red blood cells in the urine is called **hematuria** and generally indicates a pathological condition. One cause is acute inflammation of the urinary organs as a result of disease or irritation from kidney stones. Other causes include tumors, trauma, and kidney disease, or possible contamination of the sample by menstrual blood.
Ketone bodies	High levels of ketone bodies in the urine, called **ketonuria**, may indicate diabetes mellitus, anorexia, starvation, or simply too little carbohydrate in the diet.
Bilirubin	When red blood cells are destroyed by macrophages, the globin portion of hemoglobin is split off and the heme is converted to biliverdin. Most of the biliverdin is converted to bilirubin, which gives bile its major pigmentation. An above-normal level of bilirubin in urine is called **bilirubinuria**.
Urobilinogen	The presence of urobilinogen (breakdown product of hemoglobin) in urine is called **urobilinogenuria**. Trace amounts are normal, but elevated urobilinogen may be due to hemolytic or pernicious anemia, infectious hepatitis, biliary obstruction, jaundice, cirrhosis, congestive heart failure, or infectious mononucleosis.
Casts	**Casts** are tiny masses of material that have hardened and assumed the shape of the lumen of the tubule in which they formed. They are then flushed out of the tubule when filtrate builds up behind them. Casts are identified by either the cells or substances that compose them or their appearance.
Microbes	The number and type of bacteria vary with specific infections in the urinary tract. One of the most common is *E. coli*. The most common fungus to appear in urine is the yeast *Candida albicans*, a cause of vaginitis. The most frequent protozoan seen is *Trichomonas vaginalis*, a cause of vaginitis in females and urethritis in males.

Kidney Disease Is Life Threatening

Without functioning kidneys, blood composition cannot be maintained and homeostasis will be lost. Three of the most common kidney diseases are nephritis, glomerulonephritis, and polycystic kidney disease. Of these, only polycystic kidney disease is inherited. This disease causes cysts to form in the kidneys, destroying normal kidney tissue. In severe cases, the patient may require **dialysis** or even a kidney transplant.

dialysis Substance exchange via diffusion across a membrane, artificially mimicking the kidney.

Nephritis and glomerulonephritis are nephron inflammations. Nephritis and glomerulonephritis are both inflammations of the nephron of the kidney. Because the kidney is covered by the renal capsule, any inflammation within the kidney increases pressure and slows or halts filtration.

Glomerulonephritis is a general term for blockage of renal blood circulation, with subsequent shutdown of the nephrons. Nephritis is a swelling of the nephron itself, but the end results are the same. When the kidneys cannot filter blood, toxins build up and the blood becomes filled with metabolic wastes. Symptoms include nausea, dizziness, fatigue, and memory loss. If the ion and fluid balance is not restored, death can result.

Dialysis is an exchange between two solutions. As noted, dialysis is the exchange of aqueous substances between two solutions through a membrane. In effect, the nephron performs dialysis on a continuous basis. When the kidneys shut down, dialysis must continue somehow, or the blood will become toxic to the body cells.

Hemodialysis is dialysis between blood and another fluid. This is a relatively common procedure used to compensate for impaired kidney function. It can be done for extended periods, such as when the kidneys have failed and no matching donor kidney is available.

In hemodialysis, blood is withdrawn from an artery and passed across a dialysis membrane. Toxins in the blood diffuse into the prepared solution, while necessary blood plasma components are either (1) prevented from diffusing by put-

HEALTH, WELLNESS, AND DISEASE

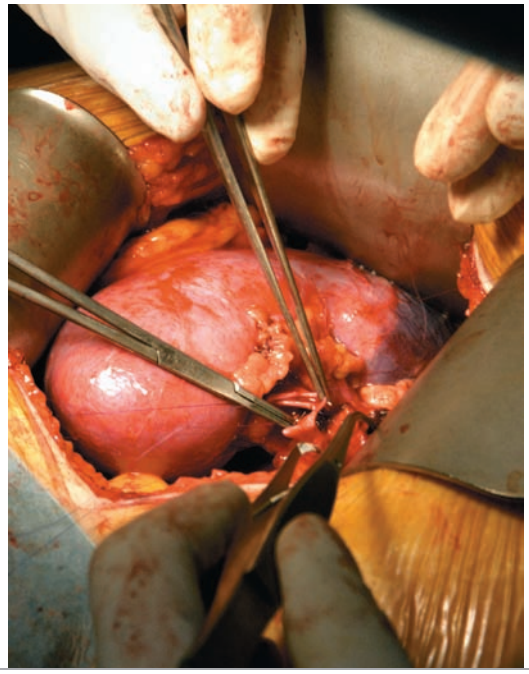
What Are the Risks in Donating a Kidney?

THE PLANNER

Some 90% of live-donor kidney transplants are successful for the recipient—but what are the risks for the donor? The immediate risks are the same as for any abdominal surgery and general anesthesia. Major complications are rare: The most common are bleeding and infection at the incision site.

Donating a kidney should have little effect on the donor's lifestyle. An individual can live and function with one healthy kidney—in fact, most recipients of kidney transplants only have the one functioning transplanted kidney. A kidney donor can work, drive, exercise, and participate in noncontact sports where collisions are infrequent, such as golf, tennis, or cross-country skiing.

A donor may return to any occupation, including public safety or the military. Generally, people return to work two to three weeks after surgery. Kidney donation has no effect on a woman's ability to conceive. Interestingly, not just anybody can donate a kidney. The donor has to have a relationship with the recipient, either through blood, marriage, friendship, or being in a shared community. People with high blood pressure, heart disease, liver disease, diabetes, cancer, sickle cell disease, human immunodeficiency virus (HIV), or hepatitis are generally not allowed to be donors.



One often overlooked "risk" to donating a kidney is being deemed ineligible for health, life, or disability insurance. Any potential donor should check with his or her insurers to make sure that donating will not change eligibility. In all, the risks to the donor are almost always outweighed by the enormous benefit to the kidney recipient.

WILEY PLUS Video

ting the same concentration of these components in the dialysis fluid as in the blood or (2) added to the blood by increasing their levels in the dialysis fluid. The dialyzed blood is then sent back to the body. The procedure takes three to four hours and must be done three times a week.

Hemodialysis is tough on the blood cells because they are passed through tubes and across membranes under pressure. If the patient requires dialysis for a long period, peritoneal dialysis may be recommended. In this procedure, 2 liters of dialysis fluid are put directly into the abdominal cavity, left to diffuse for a period, and then removed. The **peritoneum** serves as the dialysis membrane. As with hemodialysis, this procedure must be performed regularly; peritoneal dialysis is completed several times a day to sustain life.

peritoneum
Membrane lining the abdominal cavity.

Kidney transplants are highly successful. In some cases, a kidney is so diseased that it needs to be replaced. Because of the kidneys' placement, they are easy to reach surgically. The kidneys have essentially one artery and one vein. These are cut and sutured to the donor kidney. Kidney transplants are highly successful transplant operations, with almost 80% patient and organ survival rate after one year. Transplanting organs obtained by removing one kidney from a living, healthy donor rather than an accident victim have success rates above 90%. See *Health, Wellness, and Disease: What Are the Risks in Donating a Kidney?*

Obtaining nutrients, ridding wastes, and maintaining fluid homeostasis are all processes that are imperative to survival. With the digestive and urinary systems handling these vital functions, we humans can turn our attention to other occupations. Two of the more interesting of these are growth and reproduction, the topics of the next few chapters.

CONCEPT CHECK

STOP

1. **What** are four abnormalities that may appear in a urinalysis? **What** do they indicate?
2. **What** is dialysis? **How** does hemodialysis work?

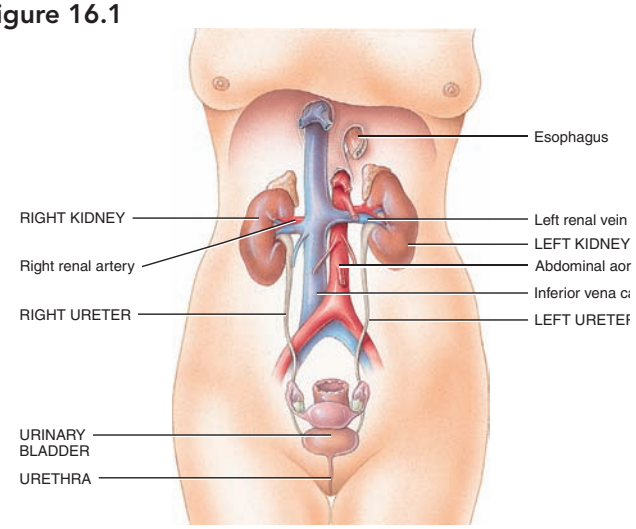
Summary

THE PLANNER

1 The Kidneys Are the Core of the Urinary System 432

- The urinary system is responsible for maintaining fluid homeostasis, ion balance, and blood calcium concentration and for removing fluid waste from the body.
- As shown in this diagram, the system includes the paired kidneys, the paired ureters, the urinary bladder, and the urethra.

Figure 16.1



Anterior view

- A **nephron** is composed of a glomerular capsule surrounding the glomerulus, a proximal convoluted tubule, a loop, and a distal convoluted tubule connected to a collecting duct. Each portion of the tubule has a distinct role in filtering blood, balancing ions and pH, and removing wastes.

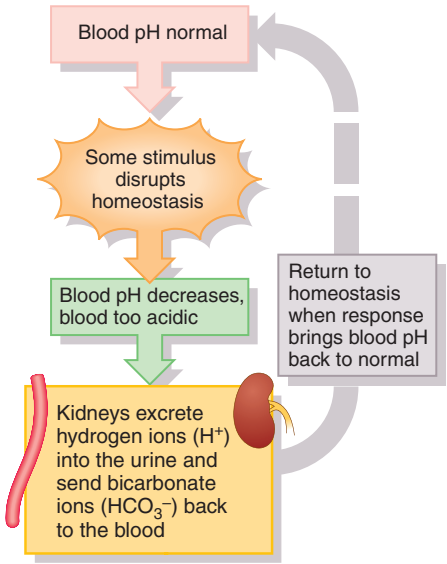
2 Urine Is Made, Transported, and Stored 436

- The nephrons are the functional units of the urinary system. It is here that 180 liters of fluid per day are filtered and maintained.
- Glomerular filtration depends on blood pressure, capsular hydrostatic pressure, and osmotic pressure of the blood. The filtrate is captured in Bowman's capsule and passed to the PCT, where most of the necessary nutrients and water are reabsorbed. The loop of the nephron extends into the middle of the kidney and assists in removal of salts and water. The DCT is involved in secretion from the blood to the forming urine. The collecting ducts remove urine from the kidney.
- Urine is stored in the bladder until voided. After 300 ml of urine fills the bladder, the micturition reflex is stimulated. The voluntary, external urinary sphincter determines when voiding takes place. Incontinence is the loss of this control. The female urethra is shorter than the male urethra, leading to a higher incidence of urinary tract infection in females.

3 The Urinary System Maintains the Body's Fluid and Solute Balance 442

- Hormones regulate the amount of water and ions excreted with the urine. ADH prevents the loss of water, causing the production of concentrated urine. Aldosterone regulates sodium reabsorption, effectively removing water and sodium from the body. ANP and BNP work to maintain blood volume and blood pressure.
- The kidneys and respiratory system combine to control blood pH, as shown here. The urinary system can remove acidic and basic substances from the fluid and flush them from the body, with permanent results. If the blood is too acidic, the kidneys can excrete hydrogen ions and send bicarbonate ions back to the blood. If the blood is too basic, the kidneys will return hydrogen ions to the blood and excrete bicarbonate ions.

Figure 16.10



4 Life-Threatening Diseases Affect the Urinary System 446

- Dialysis is the exchange of aqueous substances between two solutions through a membrane. In effect, the entire nephron performs dialysis with the peritubular capillaries on a continuous basis.
- When the kidneys shut down, dialysis must continue somehow, or the blood will become toxic to the cells of the body. Dialysis machines permit dialysis to occur outside the body.

Key Terms

- calcium oxalate 439
- casts 446
- constipation 442
- dialysis 448
- external sphincter muscle 440
- facilitated diffusion 438
- incontinence 441
- internal urethral sphincter 440
- microvilli 438
- nephron 434
- nitrogenous wastes 433
- osmolarity 442
- peritoneum 449
- peritubular capillaries 434
- secreted 439
- solute 442

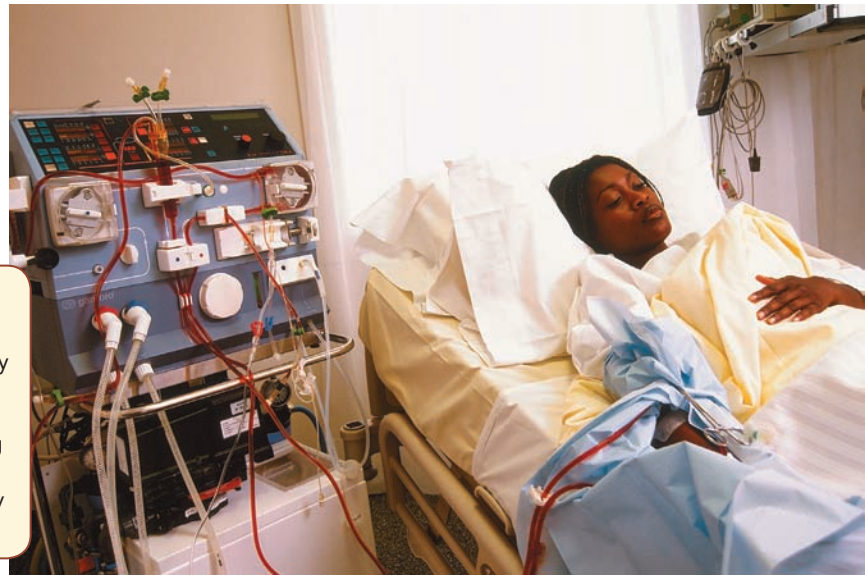
Critical and Creative Thinking Questions

1. Imagine that you contracted a urinary tract infection and did not treat it. Trace the pathway of the bacteria as it moves up the urinary system. What structures in the kidneys would you expect to be damaged by the bacteria?
2. Many home pregnancy tests look for a specific protein in the urine. This compound is present only in pregnant women. Why do the tests recommend using first morning urine? How is that different from urine produced and excreted at midday?
3. Caffeine and alcohol both block the secretion of ADH from the posterior pituitary gland. Explain what this does to fluid balance. Does it make sense to drink caffeine before an athletic event? Explain why a cold beer might not be such a great idea on a hot afternoon.
4. CLINICAL CLICK QUESTION
   Kawika was slightly overweight, and his cholesterol level was high enough that he was on medication to help lower it. Because he was trying to lose weight, Kawika had increased his exercise regime, which led to painful muscles most evenings. To alleviate the muscle aches he was feeling, Kawika began taking a few ibuprofen daily. Much to his surprise, instead of getting stronger Kawika felt progressively weaker and more tired. He was short of breath, and felt "ballooned" most mornings. His hands and feet seemed to swell overnight, causing him discomfort as he began his day. As these odd symptoms continued, Kawika's heartbeat became irregular and he began to experience mental confusion. Alarmed by these developments, Kawika visited his physician. Blood work indicated that he had high levels of potassium, low bicarbonate levels, and a decrease in red blood cells. Waste products were building up in his blood, and his BUN and creatinine levels indicated serious trouble. What diagnosis will Kawika's physician hand him? What clues indicate that this is a problem of kidney function? What might have caused Kawika's kidneys to fail? What treatment regime might his physician prescribe before trying kidney transplant surgery? For help with Kawika's diagnosis and treatment, visit Medicinenet.com and search for kidney failure (http://www.medicinenet.com/kidney failure/article.htm - tocb).

5. Assume that you were given the following results from a series of urinalysis tests. What would each test indicate?
   - Cloudy urine, above-normal specific gravity, high white blood cell count, many transitional epithelial cells
   - Presence of protein, casts, and hemoglobin
   - Presence of glucose and ketones (ketones are a by-product of the digestion of body proteins)
   - Pale yellow color, pH 6.3, specific gravity 1.015, no RBCs, no proteins

What is happening in this picture?

In the rare event that your kidneys shut down, your blood and interstitial fluid would become filled with cellular waste products. These products are toxic to the cells that produced them, and if not removed, would cause cell death and eventually organ failure. To prevent such dire consequences on a short-term basis, some of the functions of the kidneys can be mimicked through dialysis. In this picture, hemodialysis is being performed.



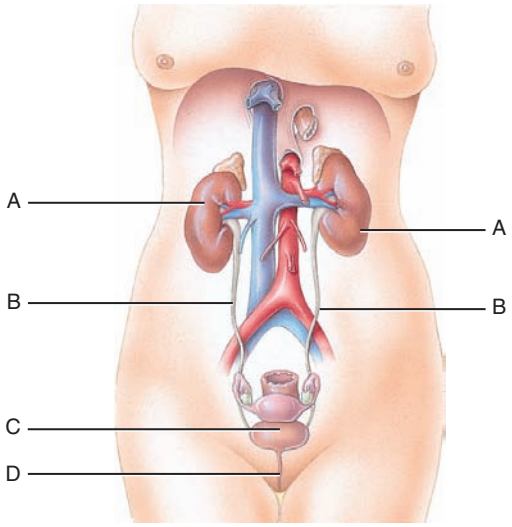
Think Critically

1. What functions of the kidney are NOT handled via hemodialysis?
2. What ions would you expect to be in the dialysis fluid? What would you expect the pH of this fluid to be? What would the specific gravity be? Would the dialysis fluid color matter?
3. Explain how the principles of filtration, osmosis, and diffusion are at work in a healthy nephron. Compare this to the principles underlying the functioning of the dialysis machine.
4. Looking at the apparatus necessary to complete dialysis, explain why this procedure is detrimental to the formed elements of the blood.

Self-Test

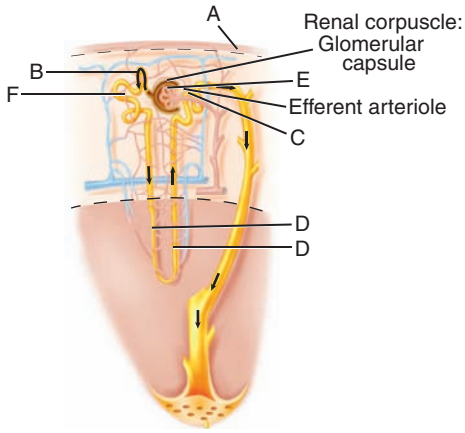
1. Which of the following is NOT a specific function of the urinary system?
   a. production of urine
   b. maintenance of blood pH
   c. maintenance of blood volume
   d. maintenance of red blood cell levels

2. The function of the structure indicated as C is _____.
   a. filtration of blood
   b. transport of urine within the body
   c. transport of urine from the body
   d. storage of produced urine



3. The correct sequence of blood vessels through the kidney is _____.
   a. renal artery → afferent arteriole → efferent arteriole → peritubular capillaries → renal vein
   b. renal vein → renal artery → peritubular capillaries → interlobular veins
   c. renal artery → peritubular capillaries → efferent arteriole → afferent arteriole → renal vein
   d. renal artery → efferent arteriole → peritubular capillaries → interlobular artery → renal vein

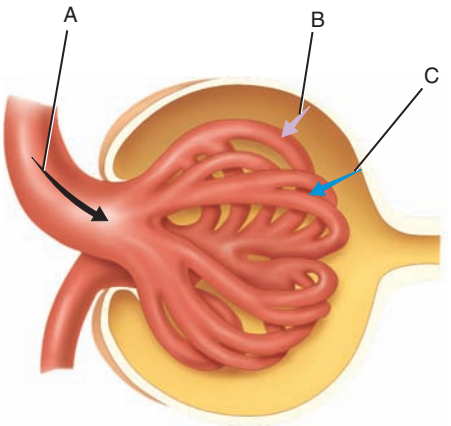
Questions 4 and 5 relate to the following diagram.



4. The function of the structure labeled B is to _____.
   a. filter blood
   b. collect filtrate
   c. reabsorb necessary nutrients
   d. secrete unwanted large waste products

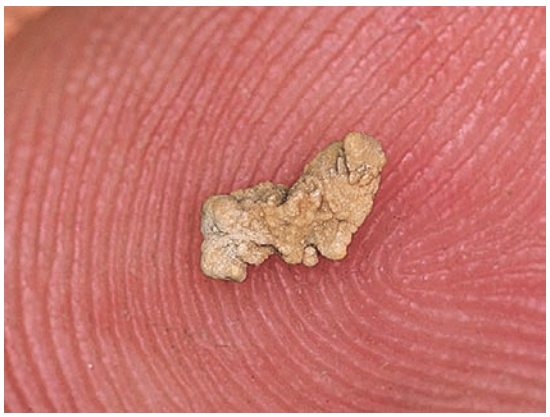
5. In the above figure, label E indicates the _____.
   a. PCT
   b. loop of Henle
   c. DCT
   d. glomerulus

6. When blood is filtered through the glomerulus, the two forces opposing movement into the nephron are _____.
   a. A and B
   b. B and C
   c. A and C
   d. All of these forces oppose movement into the capsule.



7. Most of the filtered water, and hopefully all of the filtered glucose, is returned to the bloodstream at the _____.
   a. PCT
   b. DCT
   c. loop of Henle
   d. collecting duct

8. The structure shown below is formed when _____.
   a. overly dilute urine is produced
   b. overly concentrated urine is produced
   c. kidney failure is experienced
   d. too many calcium-rich foods are consumed



9. The urethra of females carries both urine and reproductive fluids.
   a. True
   b. False

10. Dilute urine is produced when _____.
   a. ADH is present
   b. ADH is absent
   c. solutes are added to the forming urine
   d. water is removed from the collecting ducts

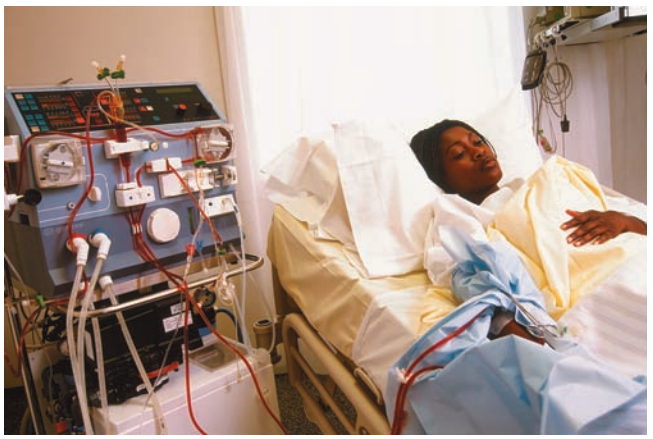
11. If you drink more water than you need, _____ will be secreted and you will lose water through the urinary system.
   a. ADH
   b. ANP
   c. aldosterone
   d. both ANP and aldosterone

12. Both caffeine and alcohol serve as diuretics, causing the production of copious dilute urine.
   a. True
   b. False

13. The compound most important in driving respiration rates and depth of breathing is _____.
   a. oxygen
   b. bicarbonate ions
   c. carbon dioxide
   d. hydrogen ions

14. Urinalysis is able to detect all of the following EXCEPT _____.
   a. vitamin supplementation
   b. illegal drug use
   c. viral infection
   d. metabolic kidney disorders

15. During the procedure shown here, if a physician wants to remove excess potassium from the blood, she or he must include a _____ of potassium in the dialysis fluid than the level that occurs in the blood.
   a. higher level
   b. lower level



THE PLANNER

Review your Chapter Planner on the chapter opener and check off your completed work.

17 The Endocrine System and Development

"Mom, I need some new jeans," Marc called from his room. The 15-year-old opened his bedroom door and handed out a pair of jeans that were new just two months earlier. "These are too small," he claimed.

"Is that possible? And why does his voice sound so full—does he have a sore throat?" his mother fretted, folding the pants. She sat back and thought about her little boy. As recently as last summer, he was a small guy, running after his older brother, scraping his knees, and relentlessly trying improbable jumps on his skateboard. Now just a few months later, he seems tremendously tall, with thicker limbs and a deeper voice.

In fact, the rapid growth of bone and muscle at this age is perfectly normal, as is the alteration in the boy's voice. Marc is maturing quickly, changing in appearance and physical ability. What is causing this predictable sequence of transformations in growth and development? "Maybe I am feeding him too much," his mother sighed as she got up, put away the undersized jeans, and began to prepare yet another oversized meal for her growing teenager.

Growth spurts usually occur earlier for girls than boys, creating an awkward time for both sexes for a few years. It is the endocrine system that is in charge of these sudden changes, and it is a fascinating system indeed.

CHAPTER OUTLINE

Hormones Are Chemical Messengers 456

- There Are Two Main Classes of Hormones
- Hormones Need Tight Controls

The Endocrine Glands Secrete Directly into the Bloodstream 461

- The Hypothalamus and the Pituitary Are the Masters of the Endocrine Universe
- The Adrenal Glands Play Multiple Hormonal Roles
- The Thyroid Affects Energy and Calcium Metabolism
- The Parathyroid Glands Also Control Blood Calcium
- The Thymus and Pineal Glands Are Most Active in Infants and Children
- The Pancreas Is Both an Endocrine and an Exocrine Gland
- Other Organs Have Endocrine Functions

Development Takes Us from Infancy to Adulthood 474

- The Newborn Baby and Infant Are Dependent Beings
- Childhood and Puberty Are Times of Almost Steady Growth
- Adulthood Is Usually the Longest Stage

CHAPTER PLANNER

- ❑ Study the picture and read the opening story.
- ❑ Scan the Learning Objectives in each section: p. 456 ❑ p. 461 ❑ p. 474 ❑
- ❑ Read the text and study all figures and visuals. Answer any questions.

Analyze key features

- ❑ Process Diagram, p. 457 ❑ p. 459 ❑ p. 470 ❑
- ❑ Biological InSight, p. 462
- ❑ I Wonder..., p. 467
- ❑ What a Scientist Sees, p. 469
- ❑ Health, Wellness, and Disease, p. 478
- ❑ Ethics and Issues, p. 479
- ❑ Stop: Answer the Concept Checks before you go on: p. 460 ❑ p. 474 ❑ p. 479 ❑

End of chapter

- ❑ Review the Summary and Key Terms.
- ❑ Answer the Critical and Creative Thinking Questions.
- ❑ Answer What is happening in this picture?
- ❑ Answer the Self-Test Questions.

17.1 Hormones Are Chemical Messengers

LEARNING OBJECTIVES

1. **Define** the function of the endocrine system.
2. **Differentiate** between steroid and nonsteroid hormones.
3. **Briefly** explain how hormones are controlled.

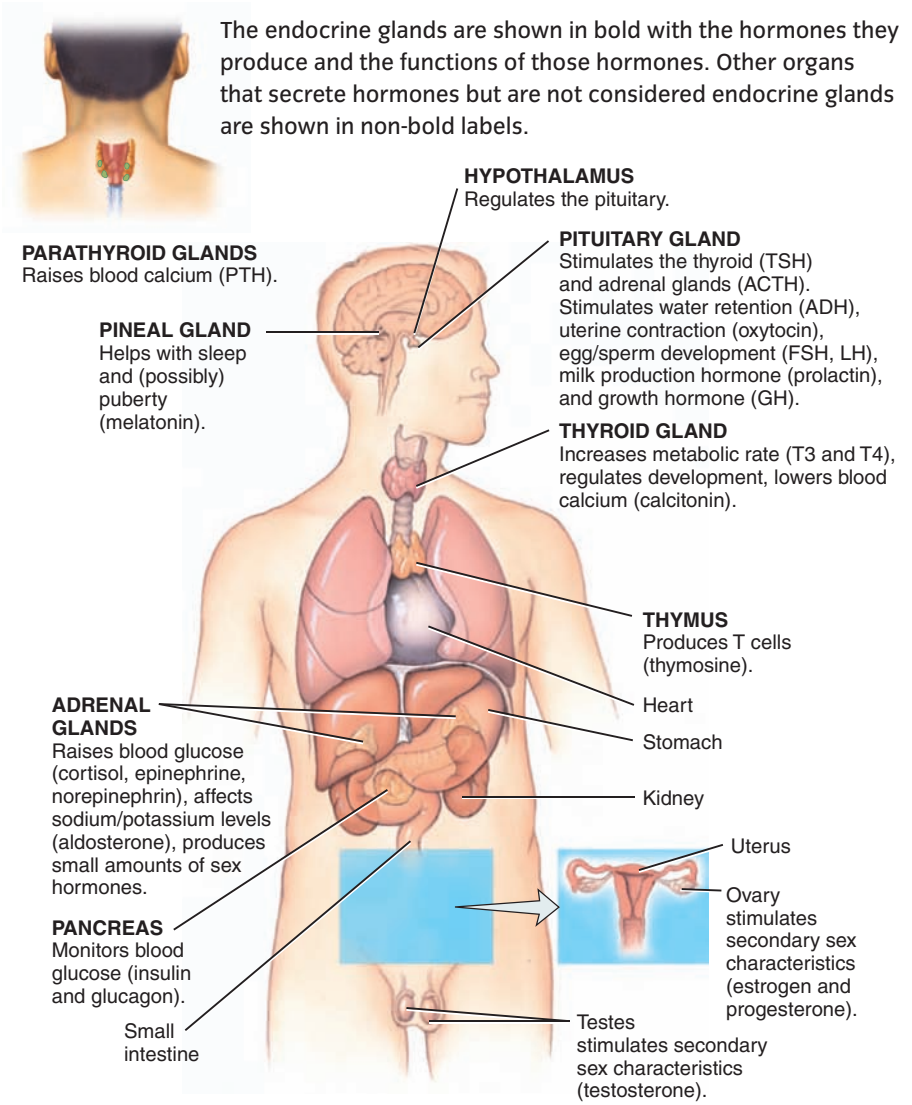
Life is a series of precisely timed processes. We are born, we grow, we become sexually mature, we reproduce, and we age. All these changes require precise, long-range timing of events over years and permanent, predictable interactions among body systems. Controlling these stages is the job of the **endocrine system**. This odd collection of organs and tissues communicates with the cells using chemical messengers called **hormones**.

At first blush, the endocrine system seems simple enough. When we are ready for a protein to be formed, or a series of reactions to begin, we merely activate a hormone. However, when you begin to focus on hormonal control, plenty of questions arise. How do hormones work at the cellular level? Why do some hormones affect the output of other hormones or affect only certain tissues? How can one hormone have many different effects?

The endocrine system is built quite differently from the other systems we have viewed, since it is mainly a group of separate structures called **endocrine glands** but also contains some organs and tissues that secrete hormones but are not considered glands—including the kidneys, stomach, liver, skin, ovaries/testes, heart, and small intestines. The endocrine system operates differently from the nervous system in that the hormones get to almost every cell in the body (unlike individual nerves with their specific paths), and it usually takes much more time for hormones to take effect than nerve firings.

The endocrine glands and the hormone-secreting organs and tissues together all form the endocrine system and are connected by the cardiovascular system. An endocrine gland secretes its products directly into the bloodstream rather than through ducts to the surface of the gland. The endocrine system is also tied directly to the nervous system, as we will see. The main glands and organs of the endocrine system are shown in Figure 17.1.

Overview of the endocrine system • Figure 17.1



The products of endocrine glands are hormones. You already know the names of several hormones, such as testosterone, estrogen, and adrenaline (the more common name for epinephrine, not to be confused with a trademarked drug, Adrenalin). Hormones are chemically active compounds that are produced in one area of the body but have their effect elsewhere. The cells that hormones act upon are called their **target cells**. Hormones are responsible for the many sequential changes of growth and maturation. They are also agents of response when homeostasis is disrupted. Hormones maintain fluid balance, control calcium and glucose levels in the blood, assist in tissue repair, maintain basal metabolic rate, and assist in digesting food. They can do all of this because hormones are carried to virtually all cells of the body via the bloodstream. They cause an effect only in their specific target cells. Interestingly, one hormone can have many different target cells; however, the overall effect of the hormone will be the same. For example, growth hormone causes muscle tissue to enlarge, bone tissue to increase matrix production, and glycogen stores to be released to fuel the increased protein production. All of these effects work together to increase body size.

There Are Two Main Classes of Hormones

The two main classes of hormones are steroid hormones, which are structurally related to cholesterol, and nonsteroid hormones, which are composed mainly of amino acids. The main difference between these classes is solubility. Steroid hormones, including testosterone and estrogen, are lipid-soluble, so they can pass directly through the phospholipid bilayer of cell membranes. Nonsteroid hormones are not lipid-soluble, so they cannot penetrate the cell membrane. This single difference translates into completely different modes of action.

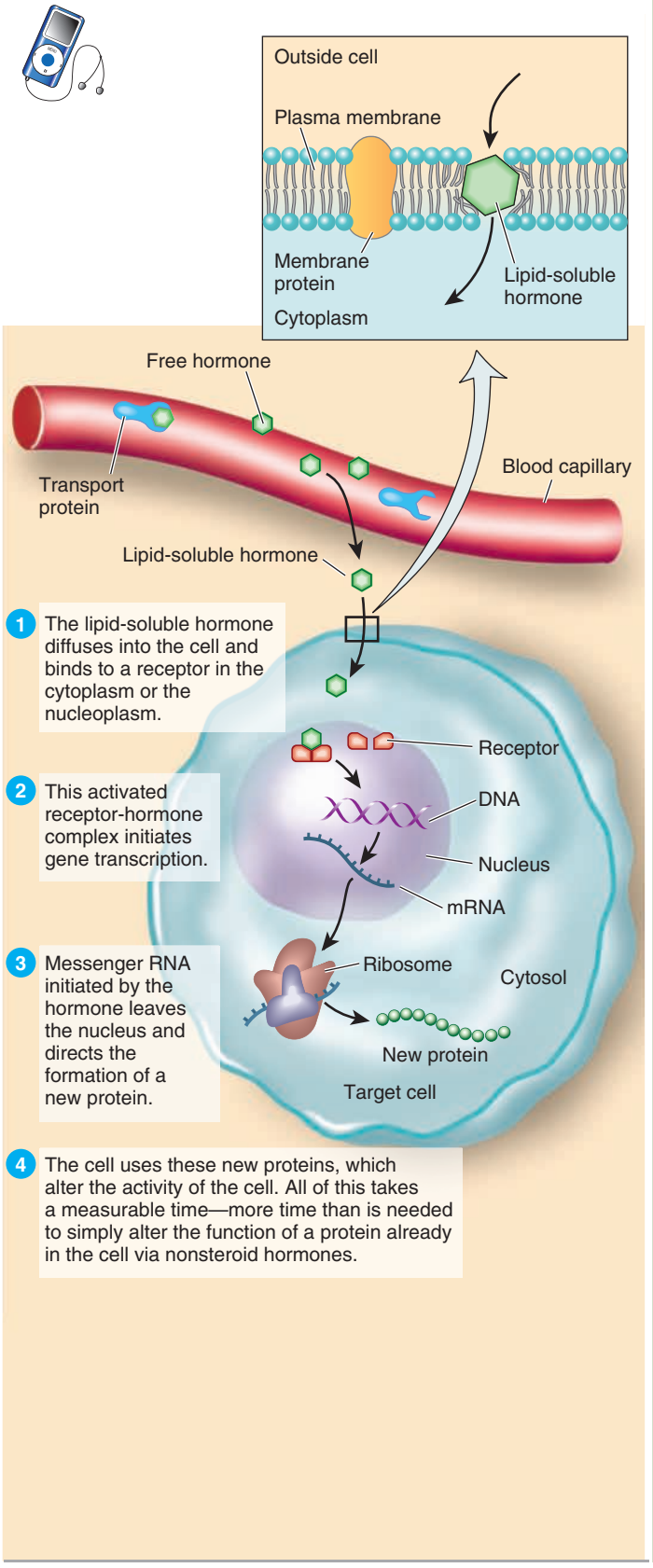
Steroid hormones enter the cell without help.

Because steroid hormones are lipid-soluble, they can pass directly through cell and nuclear membranes of their target cells, reaching specific receptors in the cytoplasm or nucleoplasm. Once the hormone binds to its receptor, it forms a receptor-hormone complex. This complex affects the transcription of genes and either upregulates (increases) or downregulates (decreases) the production of specific proteins. The change in production rate shifts the complement of proteins inside the cell, as seen in Figure 17.2.

PROCESS DIAGRAM

THE PLANNER

Steroid hormone activity • Figure 17.2



Give a toddler a set of building blocks, and you will usually be rewarded with a proudly displayed, three-block tower. If you then give the child additional blocks of different shapes, you will be presented with an entirely new building. The shape of the blocks determines the shape of the building. In much the same way, the protein complement of the cell determines its function. Directing the construction of proteins, after all, is what genes do—so in this sense, hormones rule protein production.

This process, from gene activation to protein production to final effect, can take anywhere from a few minutes to many hours. The process requires reading a gene, following the instructions presented to form a specific protein, and then using the newly created protein to alter the activities of the target cell. For this reason, steroid hormones act relatively slowly when compared with nonsteroid hormones or neural impulses.

The common human steroid hormones are listed in Table 17.1. For each hormone, you will find the organ that produces it, the cells it targets, and the results of its actions.

Nonsteroid hormones are fast acting and powerful. Nonsteroid hormones, such as epinephrine, thyroid hormones, and antidiuretic hormone, can affect target cells much more quickly than steroid hormones because they affect the activity of proteins that are already present in those cells. The gene has already been read and the protein formed. The necessary protein is merely waiting to be packaged for use. Nonsteroid hormones are water-soluble, so they are easily transported to the cell in blood or interstitial fluid. However, water-soluble hormones cannot diffuse across the phospholipid bilayer of the target cell.

To overcome this obstacle, nonsteroid hormones act on specific receptors that stud the surface of target cells. These receptors are integral membrane proteins, often with an associated but inactive molecule attached to the cytoplasmic side of the protein. Hormone binding to the exterior of the integral protein changes the receptor and activates the associated inactivated molecule, releasing it into the cytoplasm. The released molecule, usually **cyclic AMP (cAMP)**, becomes a second messenger that carries information from the hormone (the first messenger) to the machinery of the cell. cAMP in turn activates an enzyme, often a **kinase**, that can alter various biochemical and cellular pathways.

cyclic AMP (cAMP) A form of adenosine monophosphate in which the phosphate appears in ring formation, carrying little energy (not enough to harness for metabolic processes).

kinase A group of enzymes, all of which transfer a phosphate from one compound to another.

Frequently, a series of enzyme activations occurs after an aqueous hormone binds. This activation takes only seconds or at most less than a minute, compared to the minutes to hours needed to produce a new protein via a steroid hormone. Another benefit of nonsteroid hormone activity is that at each step, the original signal is amplified, as shown in Figure 17.3. One bound hormone can eventually cause the activation of many enzymes. Because the effects of a small amount of hormone can be greatly exaggerated, nonsteroid hormones are quite potent.

Steroid hormones Table 17.1

Hormone	Organ that produces it	Target cells	Effects
Androgens and estrogens	Ovaries, testes, adrenal cortex	Most cells of the body	Stimulate the development of male or female secondary sexual characteristics
Mineralocorticoids	Adrenal cortex	Kidneys	Increase absorption of sodium and water by the kidneys, accelerate potassium loss
Glucocorticoids	Adrenal cortex	Most cells of the body	Promote liver formation of glucose and glycogen, release amino acids from muscle, anti-inflammatory effects
Calcitriol	Kidneys	Intestinal lining	Stimulates calcium and phosphate absorption, inhibits PTH release

Nonsteroid hormones include very small compounds derived from single amino acids, as well as compounds composed of short chains of amino acids. These larger hormones are called peptide homones. Despite the size difference, both varieties are water-soluble and therefore use the same general pathway.

The common nonsteroid hormones in the body are listed in **Table 17.2** on the following page. We will return to these hormones when discussing the endocrine glands.

Hormones Need Tight Controls

The action of a hormone is entirely dependent on the target cell, so a particular hormone can have widely varying effects on different tissues. For example, **somatostatin** prevents the secretion of growth hormone in the hypothalamus, helps regulate digestive function in the abdominal cavity, and prevents the pancreas from releasing hormones that regulate blood sugar. Notice that when somatostatin is released, this entire suite of effects is likely, unless something changes in the target tissues.

somatostatin
A water-soluble hormone that prevents the secretion of growth hormone; literally to "keep the body the same" (*soma* = body).

Regardless of the hormone class, an endocrine gland's activity must be controlled. Recall from Chapter 1 that homeostasis is usually maintained via negative feedback, and this type of regulation applies to most hormones. The hormone's effect on the body may diminish the trigger that stimulated its production, or a second hormone may oppose the action of the first. In the simplest example of negative feedback, the endocrine system acts as the control center, responding to changes in blood or interstitial fluid chemistry. The hormone connects the control center and the effector (its target cells). Activation of the target cells shuts down the original stimulus, and homeostasis is restored.

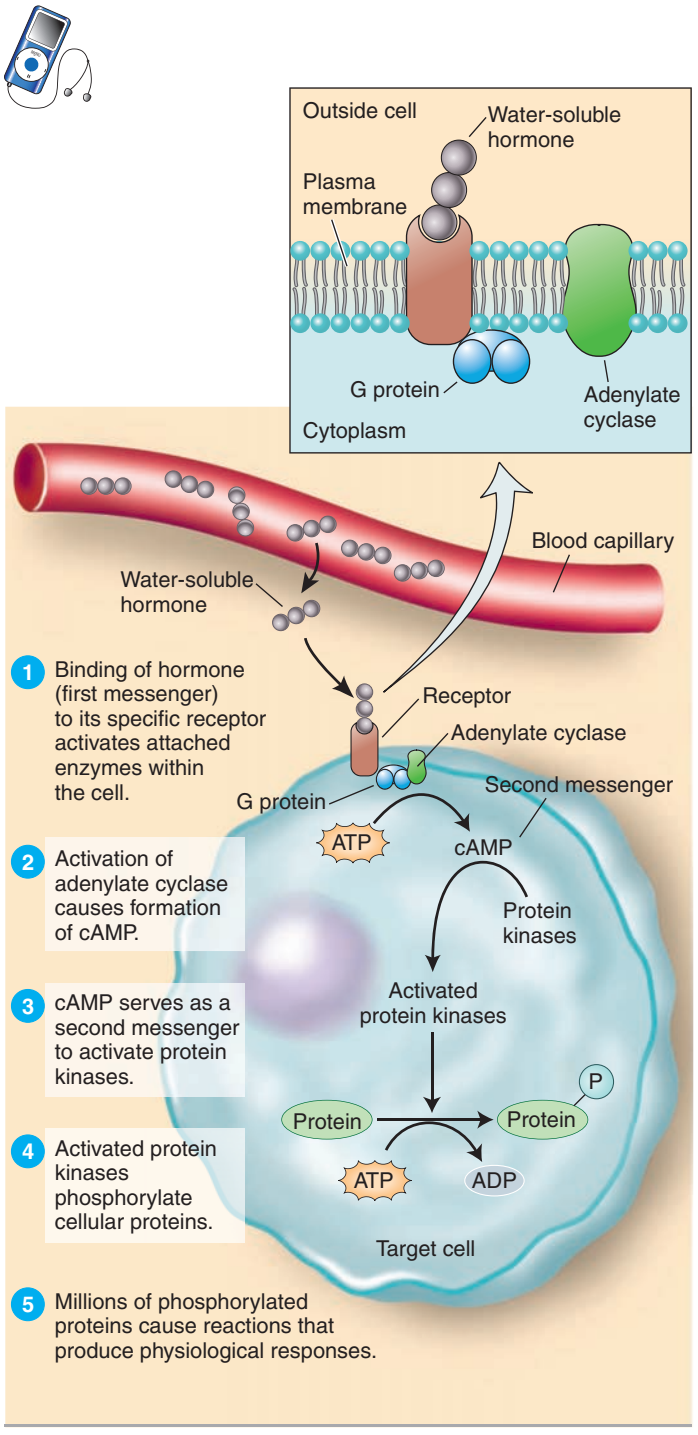
The situation becomes more complicated when several hormones interact. These hormones can either directly or indirectly stimulate or inhibit one another, resulting in webs of interaction. The net result is the same, however: Homeostasis is maintained via negative feedback.

PROCESS DIAGRAM

THE PLANNER

Nonsteroid hormone activity • Figure 17.3

Water-soluble hormones diffuse from the blood to receptors on the surface of the target cell. When bound, these hormones cause proteins within the cell to activate.



Nonsteroid hormones Table 17.2

Hormone	Organ that produces it	Target cells	Effects
Epinephrine and norepinephrine	Adrenal medulla	Most cells of the body	Increase cardiac activity, blood pressure, and blood glucose levels; release stored lipids
Thyroid-stimulating hormone (TSH)	Anterior pituitary	Thyroid gland	Causes secretion of thyroid hormones
Luteinizing hormone (LH)	Anterior pituitary	Immature egg cells of ovary; interstitial cells of testes	Triggers ovulation in ovary, secretion of testosterone in testes
Follicle-stimulating hormone (FSH)	Anterior pituitary	Immature egg cells of the ovary; immature sperm cells of the testes	Stimulates the development of eggs and production of estrogen, development of sperm
Adrenocorticotropic hormone (ACTH)	Anterior pituitary	Adrenal cortex	Stimulates secretion glucocorticosteroids
Growth hormone (hGH)	Anterior pituitary	All cells of the body	Promotes growth, protein synthesis, lipid movement
Melanocyte-stimulating hormone (MSH)	Anterior pituitary	Unknown, perhaps melanocytes	In melanocytes, triggers increased melanin production
Prolactin (PRL)	Anterior pituitary	Mammary glands	Stimulates production of milk
Thyroxine (T4)	Thyroid gland	Most cells of the body	Increases energy utilization, oxygen consumption, growth, and development
Calcitonin	Thyroid gland	Bone, kidneys	Decreases calcium concentration in body fluids
Melatonin	Pineal gland	Hypothalamus	Inhibits secretion of GnRH (gonadotropin-releasing hormone, which governs the release of FSH and LH)
Oxytocin	Hypothalamus	Uterus and mammary glands in females; vas deferens and prostate gland in males	Triggers smooth muscle contractions during labor, milk release, and male ejaculatory event
Antidiuretic hormone	Hypothalamus	Kidneys	Causes reabsorption of water, elevation of blood pressure
Insulin	Pancreas	Most cells of the body	Promotes uptake of glucose; stimulates storage of lipids
Glucagon	Pancreas	Liver, adipose tissues	Activates lipid reserves; elevates blood glucose levels
Parathyroid hormone	Parathyroid glands	Bone, kidneys	Increases calcium concentration in body fluids
Erythropoietin	Kidneys	Red bone marrow	Stimulates the production of RBCs
Inhibin	Testes, ovaries	Anterior lobe of the pituitary gland	Inhibits secretion of FSH

CONCEPT CHECK

1. **What** is the function of the endocrine system?
2. **How** do nonsteroid hormones differ from steroid hormones?
3. **How** are hormones controlled?

17.2 The Endocrine Glands Secrete Directly into the Bloodstream

LEARNING OBJECTIVES

1. **List** the major endocrine glands and their hormones.
2. **Define** the relationships among endocrine glands.

Hormones usually get released into our bloodstreams in short bursts when an endocrine gland is stimulated by a signal from the nervous system or another endocrine gland. When the stimulation stops, the concentration of the hormone in our blood drops. This negative feedback system usually ensures that the hormone is not overproduced or underproduced.

The endocrine system has several key components. These are:

- The masters of the endocrine universe—the hypothalamus and pituitary
- The multifunctional adrenal glands, responsible for our fight-or-flight response to stress and danger
- The thyroid, matching our energy level with our immediate energy needs
- The parathyroid, controlling our blood calcium
- The thymus, pineal gland, pancreas, and other glands, organs, and tissues making the hormones that allow us to respond appropriately to our environment

We will now discuss the various glands and the hormones they secrete.

The Hypothalamus and the Pituitary Are the Masters of the Endocrine Universe

The endocrine system is directly tied to the nervous system through the hypothalamus. This bit of the forebrain monitors water and ion balance, body temperature, and carbohydrate metabolism. The hypothalamus physically connects with the pituitary gland and shares a portal circulation route. Recall that a portal system is a circulation route that flows from a capillary bed to veins to another capillary bed. The hypothalamus secretes releasing and inhibiting factors into a portal system of capillaries that are connected directly to the capillaries of the anterior pituitary gland. This portal system allows quick delivery of hypothalamic regulatory factors to the pituitary gland and thereby permits rapid response of the pituitary cells through the release of pituitary hormones.

The pituitary gland hangs from the hypothalamus into a depression in the sphenoid bone, as shown in **Figure 17.4** on the following page. It is composed of two sections, the anterior pituitary gland and the posterior pituitary gland. The two parts of the pituitary gland are suspended from the hypothalamus by a thin stalk. The pituitary gland secretes **endorphins** and **enkephalins** as well as nine hormones, many of which in turn stimulate other endocrine glands. The posterior pituitary gland contains the axons of neurons that originate in the hypothalamus. These neurons secrete two hormones from the posterior pituitary gland. The anterior pituitary gland is composed of epithelial tissue and produces seven hormones, all under the control of the hypothalamus.

endorphins and **enkephalins**
Naturally occurring compounds that reduce the sensation of pain and produce a feeling of well-being.

Because the pituitary hormones affect other endocrine glands, the pituitary gland used to be called the master gland of the endocrine system. Now that we understand how the hypothalamus governs the pituitary gland, that terminology is obsolete.

The posterior pituitary gland acts in childbirth and water regulation. The posterior pituitary gland is composed of **neuroendocrine** neurons. These neurons carry nerve impulses and also produce two hormones for release into the bloodstream. The posterior pituitary gland produces **oxytocin** and **antidiuretic hormone**.

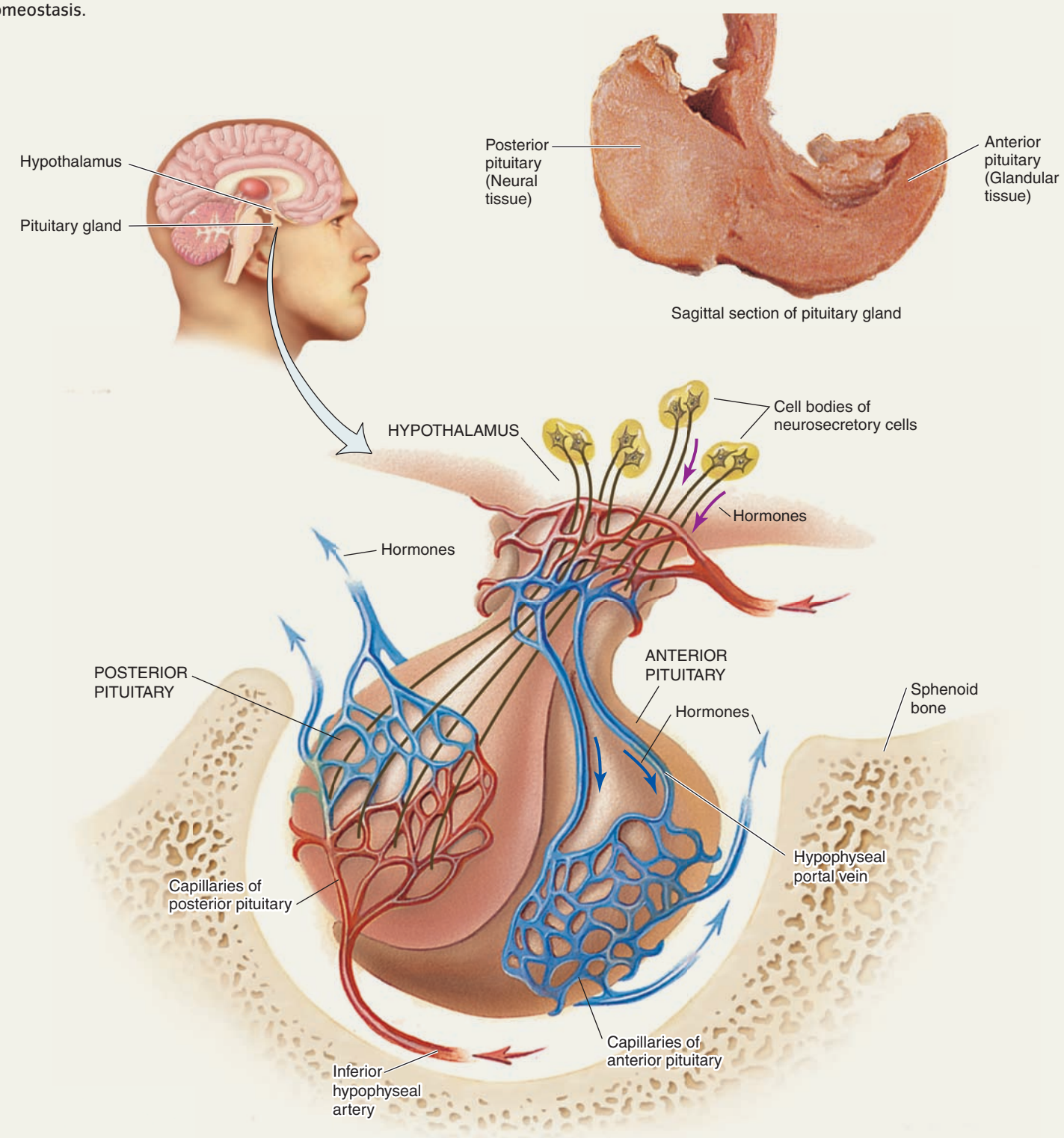
The hormone oxytocin has important roles in childbirth and lactation. This hormone initiates labor and causes cells in the mammary gland ducts to contract during the

Biological InSight

The hypothalamus and the pituitary gland • Figure 17.4

THE PLANNER

The pituitary gland is located beneath the brain, hanging from the hypothalamus. The two parts of the pituitary gland, anterior and posterior, sit within the sphenoid bone. Hormones released from the hypothalamus stimulate the pituitary gland to release a series of hormones designed to maintain homeostasis.



Relationship of the hypothalamus to the pituitary gland

Hormones of the pituitary gland Table 17.3

Hormone	Target cells	Primary action
Posterior Pituitary Gland		
Antidiuretic hormone (ADH)	Kidneys	Promotes water retention
Oxytocin	Uterus, mammary gland ducts	Triggers labor and milk let-down contractions
Anterior Pituitary Gland		
Thyroid-stimulating hormone (TSH)	Thyroid	Stimulates secretion of T3 and T4
Adrenocorticotropic hormone (ACTH)	Adrenal cortex	Stimulates secretion of glucocorticoids
Follicle-stimulating hormone (FSH)	Ovaries and testes	Promotes gamete development
Luteinizing hormone (LH)	Ovaries and testes	Triggers ovulation and testosterone production
Prolactin (PRL)	Mammary glands	Stimulates milk production
Growth hormone (hGH)	Most cells of the body	Promotes growth
Melanocyte-stimulating hormone (MSH)	Unknown, possibly brain	Unknown; in high concentrations, MSH may cause skin darkening

"milk let-down" response. This is one of the few examples of positive feedback in the human body. As labor nears, the uterus becomes more sensitive to oxytocin, reacting to small amounts of the hormone with larger contractions. During nursing, the milk let-down response is triggered by a neuroendocrine reflex. As the newborn suckles, sensory receptors in the nipple send impulses to the hypothalamus, which responds by increasing oxytocin production.

Antidiuretic hormone, or ADH, affects nephrons of the kidney. As discussed in Chapter 16, ADH prevents water loss by altering the permeability of the distal convoluted tubule cells to water. The hypothalamus initiates production of ADH when it detects low water levels in the blood. As ADH triggers target cells in the kidney, the water level in the blood increases. When the hypothalamus detects rising tissue water levels, it quits producing ADH. You can get an indication of the strength of ADH when you drink caffeine or alcohol, both of which inhibit ADH release. You may have noticed a need to urinate soon after drinking a cup of coffee. Because ADH is inhibited by caffeine, all the water collected in the distal portion of the nephron leaves the kidney for the bladder.

In diabetes insipidus, either the posterior pituitary gland does not produce enough ADH or the ADH receptors in the kidney fail. People with diabetes insipidus produce large quantities of very dilute urine. In severe cases, fluid loss can exceed 10 liters a day. If these people do not drink enough water, they may die of dehydration.

The anterior pituitary gland produces seven hormones. The anterior pituitary gland produces hormones that stimulate growth, metabolic rate, milk production, and **glucocorticoid** production. Glucocorticoids are steroid hormones that maintain mineral balance and control inflammation and stress. Once puberty begins, the anterior pituitary gland also secretes the hormones that maintain reproductive ability. These hormones are listed in Table 17.3.

Four anterior pituitary hormones—ACTH, FSH, LH, and TSH—are messenger hormones that cause target cells to secrete other hormones. These messengers travel through the bloodstream to a second endocrine gland. Once they interact with target cells on the second endocrine gland, that second gland secretes hormones that will alter homeostatic balance.

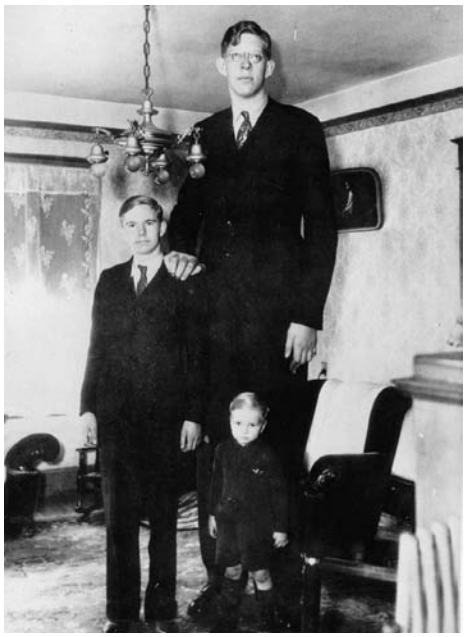
Adrenocorticotropic hormone, ACTH, has a long name that explains the hormone's action quite nicely. "Adrenocortico" indicates the cortex of the adrenal glands, those small bits of endocrine tissue atop each kidney, and the suffix *-tropic* means "acting upon." ACTH stimulates the adrenal cortex to produce glucocorticoids and **mineralocorticoids**. These two classes of hormone maintain homeostasis during stress and control glucose metabolism.

mineralocorticoids
Steroid hormones involved in maintaining water and ion balance.

Follicle-stimulating hormone (FSH) and **luteinizing hormone** (LH) are both **gonadotropins**. They stimulate the growth and functioning of the ovaries and testes, which in turn produce estrogen and testosterone. These hormones are usually not produced until age 10 to 13. A

gonadotropins
Hormones that stimulate activity in the gonads (ovary and testes).

Gigantism • Figure 17.5



Robert Wadlow had an excess of growth hormone throughout his life. The result was both an increase in overall size due to excess growth hormone production prior to puberty and the symptoms of acromegaly as production continued into adulthood.

surge in production of FSH and LH initiates puberty and the graduation from childhood to adolescence.

Thyroid-stimulating hormone (TSH) activates the thyroid to produce T3 (triiodothyronine) and T4 (thyroxin), which we will cover later in this chapter. Both hormones are involved in maintaining your basal metabolic rate. They determine how quickly and efficiently your body uses the energy you consume.

Two hormones from the anterior pituitary gland, prolactin (PRL) and human growth hormone (hGH), act directly on target tissue instead of serving as messenger hormones.

Prolactin (PRL) stimulates milk production in females. Males also produce prolactin, but the exact function is uncertain. In sexually mature male birds, prolactin is important in attaining brightly colored plumage. Prolactin is also thought to play a role in sexual dimorphism (difference between the sexes) in amphibians.

Human growth hormone affects almost every body system.

Human growth hormone (hGH) stimulates the growth of muscle, cartilage, and bone, and causes many cells to speed up protein synthesis, cell division, and the burning of fats for energy. It is manufactured by the anterior pituitary gland—and by large pharmaceutical companies.

This hormone is active at birth, then goes into overdrive during childhood and adolescence, causing bone elongation, muscle growth, and an overall increase in body mass. Although less effective after puberty, hGH is still essential to adult health. During this time, the bones have finished growing and the epiphyseal plates are sealed, so height cannot increase. However, muscles and cartilage can and do continue to enlarge. Bones can also increase in girth, strengthening the skeleton. hGH also assists in the burning of fats and amino acids when glucose stores are low.

Growth hormone noticeably stimulates growth of skeletal muscle and bone. While discussing the muscular system, we mentioned that this hormone is one substance that unscrupulous athletes abuse to chemically enhance their training. Abnormal levels of growth hormone are also produced naturally in some diseases.

If growth hormone is produced in large amounts prior to puberty, the bones and muscles will continue to grow, causing gigantism—see **Figure 17.5**. The tallest person ever measured was Robert Wadlow, the Alton Giant, who was 2.71 m (8 feet, 11 inches) tall when he died. Andre the Giant, another victim of growth hormone hypersecretion, was 1.9 m (6 ft, 3 in.) at age 12 and reached 2.23 m (7 ft, 4 in.) by adulthood.

While gigantism is rare, a different type of growth hormone hypersecretion is more common. Acromegaly is the secretion of excess growth hormone after the closure of the epiphyseal plates, when further increase in height is impossible. Acromegaly typically enlarges cartilage, causing an enlarged chin and accelerated growth of the nose, ears, and voice box, as well as a coarsening of the skin and an enlargement of the hands and feet. **Figure 17.6** shows the facial features associated with acromegaly.

Acromegaly • Figure 17.6

Richard Kiel suffered from acromegaly, which is hard to diagnose in its early stages because it is slow to develop. The diagnosis usually is made only when facial features associated with acromegaly become noticeable.

Growth hormone can also be hyposecreted during development, causing pituitary dwarfism. The growth plates close too early, organs stop growing, and childlike proportions remain throughout adulthood. Pituitary dwarfism can be treated with injections of artificial hGH. A drug company began using genetically engineered bacteria to synthesize hGH in the late 1980s, and the compound was used to treat people who made insufficient hGH. A study found that additional hGH can increase final height by an average of 7 centimeters in those whose pituitary gland does not produce enough hGH.

Gradually, the hormone saw wider use and is now being used to treat something that's not even a disease: idiopathic short stature, or ISS. *Idiopathic* means "we don't know why" and being short, well, everybody understands that part. By opening the market to ISS, the FDA helped fuel the ongoing debate over hGH treatment. Nobody questions using the hormone to treat children who do not produce enough of the hormone naturally—but should other children be treated?

Artificial hGH is produced through genetically engineering a bacterial cell, and as biotechnology becomes ever more powerful, more ethical questions are arising. Many of these questions concern the use of genetic technologies to perfect the human. What is the price of perfection? Do parents have a duty to accept healthy children as they are, or do they have the freedom—even the obligation—to "improve" their children's anatomy and physiology?

The Adrenal Glands Play Multiple Hormonal Roles

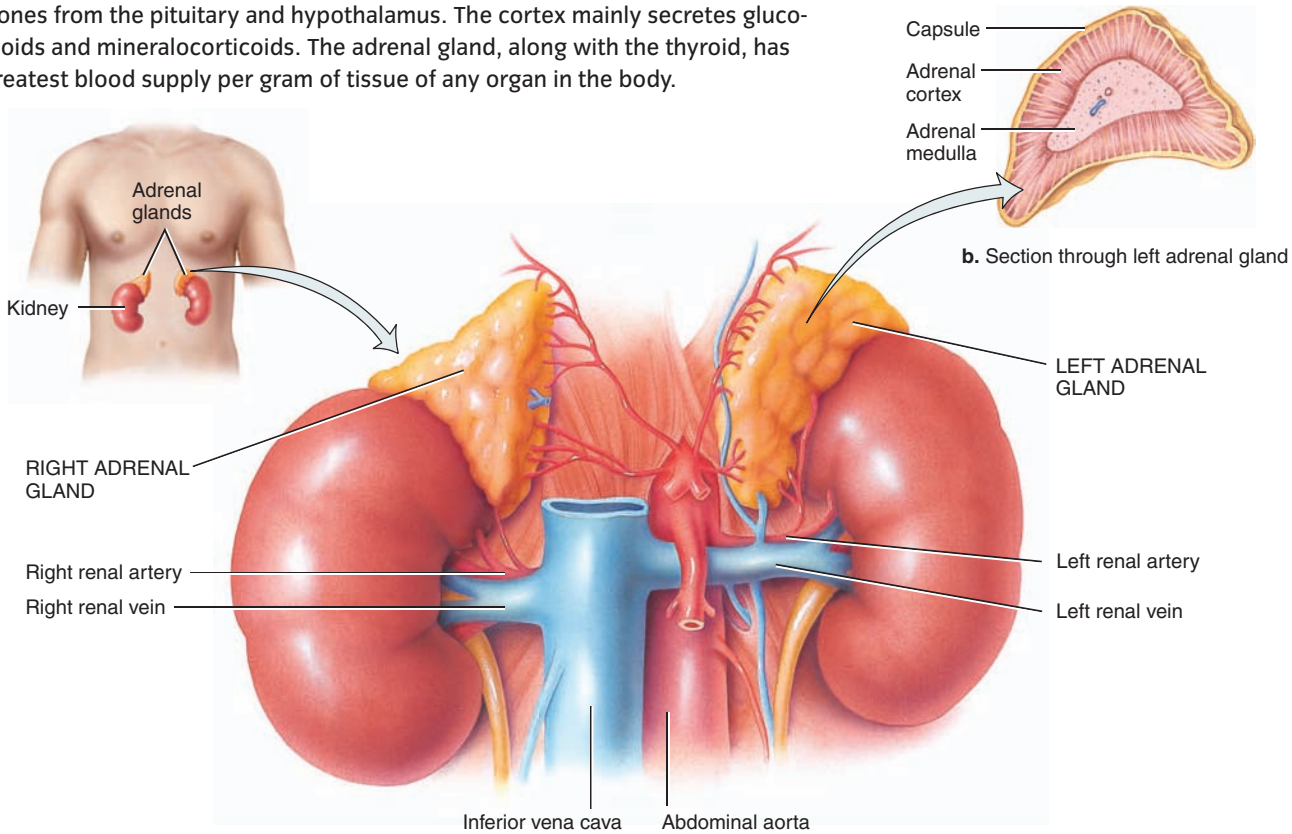
The adrenal glands, atop the kidneys, secrete a number of hormones. **Figure 17.7** shows that these glands have an outer **cortex** and an inner **medulla**. The cortex secretes glucocorticoids, mineralocorticoids, and small amounts of estrogen and testosterone. The adrenal medulla secretes epinephrine and norepinephrine, which cause the fight-or-flight reaction discussed in Chapter 9, in response to real or perceived stress.

cortex Thin outer layer of any organ.

medulla Inner portion of the organ.

External and internal anatomy of the adrenal glands • Figure 17.7

The inner core of the adrenal glands is the adrenal medulla, which secretes epinephrine and norepinephrine. The outer layer, the adrenal cortex, is regulated by hormones from the pituitary and hypothalamus. The cortex mainly secretes glucocorticoids and mineralocorticoids. The adrenal gland, along with the thyroid, has the greatest blood supply per gram of tissue of any organ in the body.



Glucocorticoids are a group of hormones involved in glucose metabolism. The glucocorticoid secretion of the adrenal cortex is **cortisol**. Cortisol is similar to glucagon in that it promotes the use of fats and proteins as energy sources. Specifically, it causes muscle tissue to break down proteins to amino acids, which the liver can convert to glucose. Cortisol is also an anti-inflammatory. You may have topical cortisol in your medicine cabinet, labeled hydrocortisone, to control itches and rashes. You should not use these products for long, however, as a high level of cortisol can suppress your immune system.

The feedback control on cortisol production is typical of the endocrine system. ACTH is released from the anterior pituitary gland when blood cortisol is low. CRH (**cortisol-releasing hormone**) is released from the hypothalamus when the cortisol level drops, causing ACTH to be produced from the anterior pituitary gland. As ACTH level increases, cortisol is produced. Rising blood levels of cortisol inhibit ACTH and CRH. These hormones fluctuate constantly around their ideal, keeping cortisol levels within a narrow range. Cortisol secretion is also affected by physical injury or emotional stress, both of which cause a marked increase in cortisol. The resulting rise in blood glucose is useful during injury repair, and the anti-inflammatory activities decrease fluid loss by capillaries, reducing tissue water retention during stress.

cortisol-releasing hormone
A compound secreted by the hypothalamus into the portal system causing release of ACTH, a pituitary hormone.

Mineralocorticoids are also secreted by the adrenal cortex.

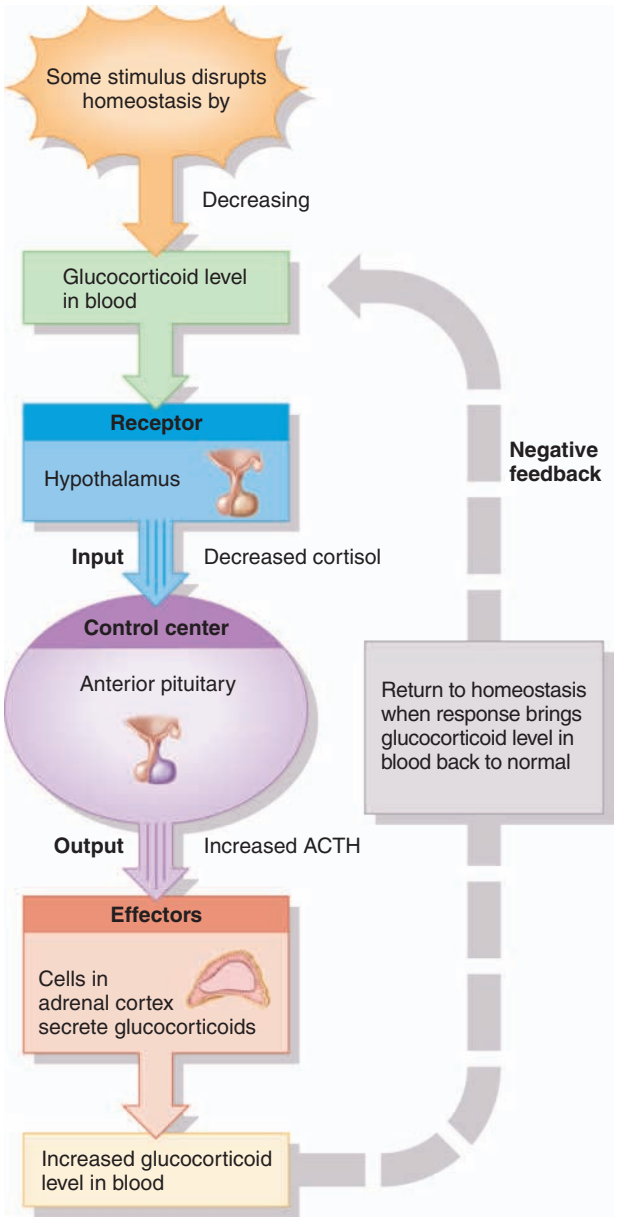
Mineralocorticoids are hormones that monitor and maintain ion balance. Sodium and potassium are closely regulated by the hormone **aldosterone**, which also affects water balance. Recall that where sodium goes, water follows. By maintaining proper sodium concentrations, aldosterone assists in maintaining correct fluid levels inside and outside cells. Aldosterone is produced when sodium and water levels are too low or potassium levels are too high. Aldosterone causes retention of sodium—and therefore water—in the kidneys by exchanging sodium ions, destined for excretion, with potassium ions. Sodium levels in the tissues increase, while potassium levels decrease. The action of this hormone is one reason athletes are told to ingest more potassium during the summer. In an attempt to retain the water lost during practice, the body produces aldosterone, which drastically lowers the potassium level, raising the risk of muscle cramps. Figure 17.8 illustrates the controls on this hypothalamus/anterior pituitary gland/adrenal cortex pathway.

There are several diseases of the adrenal gland.

Adrenal diseases include Cushing's syndrome and Addison's disease. Cushing's syndrome is caused by hypersecretion of the adrenal cortex, which puts excess cortisol in the blood. The cortisol breaks down muscle proteins and redistributes body fat (causing the typical round, flushed "moon face"), a deposit of fat at the back of the neck, and small, thin

Negative feedback regulation of glucocorticoid secretion • Figure 17.8

A low level of glucocorticoids promotes the release of ACTH, which stimulates glucocorticoid secretion by the adrenal cortex.



arms and legs. Patients also suffer blood chemistry imbalances, primarily excess glucose. Their bones become weak, and they suffer from hypertension and mood swings.

Addison's disease, the hyposecretion of glucocorticoids and aldosterone, is usually due to autoimmune destruction of the adrenal cortex. The resultant lack of glucocorticoids causes mental slowness, anorexia, weight loss, and a bronzing of the skin. President J. F. Kennedy suffered from Addison's disease while in office, but few related his tanned appearance to a disease, and his quick-witted performance at press conferences showed no sign of mental slowness.

The Thyroid Affects Energy and Calcium Metabolism

Under the influence of thyroid-stimulating hormone from the anterior pituitary gland (discussed earlier), the thyroid gland secretes two structurally similar hormones, T3 and T4 (T3 is often converted to T4 in the body). These hormones are involved in **basal metabolic rate** and help determine how quickly and efficiently you use energy. You may have noticed that some of your friends can devour enormous helpings of food without gaining weight, while others seem to gain weight from just eyeballing a slice of cake. These differences in energy use and storage are partly regulated by your friends' thyroid hormones and their resulting basal metabolic rate—see *I Wonder… Can I Figure Out My Own Basal Metabolic Rate?* for more information. Thyroxin (T4) is responsible for the cellular conversion of glucose to ATP. Higher T4 production increases basal metabolic rate, meaning that more work is done, more heat is produced, and more energy is expended. Too much or too little of these hormones can cause abnormal growth and development.

basal metabolic rate Rate of energy usage when the body is quiet, resting, and fasting.

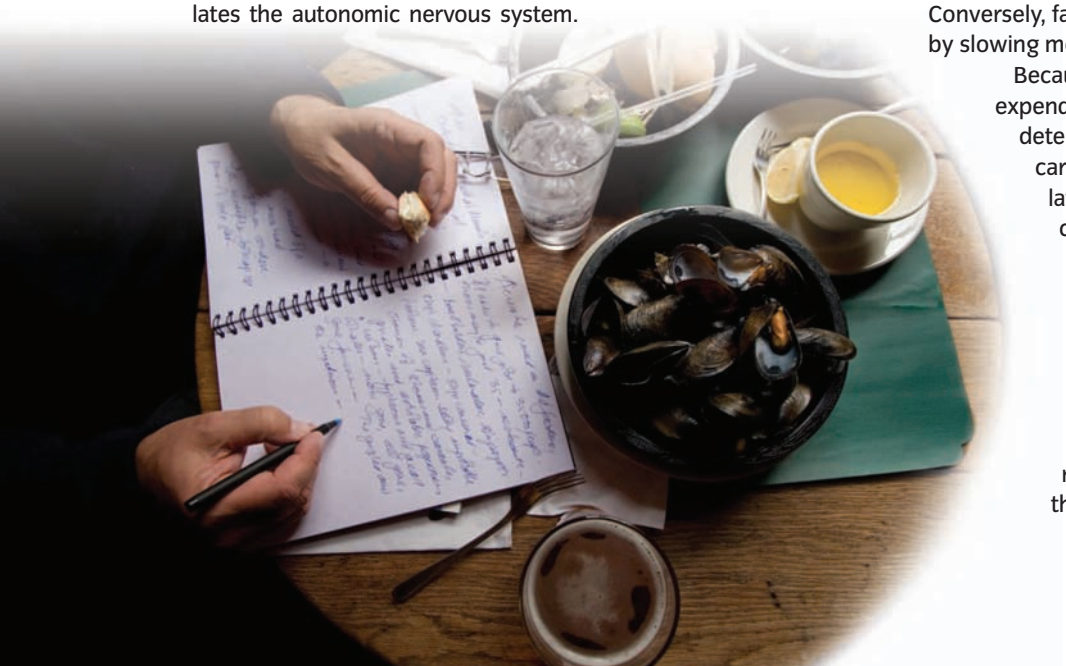
I WONDER...

THE PLANNER

Can I Figure Out My Own Basal Metabolic Rate?

Basal metabolic rate (BMR), as we have seen, is the rate of energy usage that your body needs to stay alive, without accomplishing anything more. It's the kilocalories you expend sleeping, fasting, and, to be technically accurate, probably not dreaming. In daily life, we seldom operate at BMR; this rate is a baseline to which we add the energy spent on activities like thinking, moving, and digesting.

The ultimate control on BMR is the hypothalamus, which regulates the autonomic nervous system.



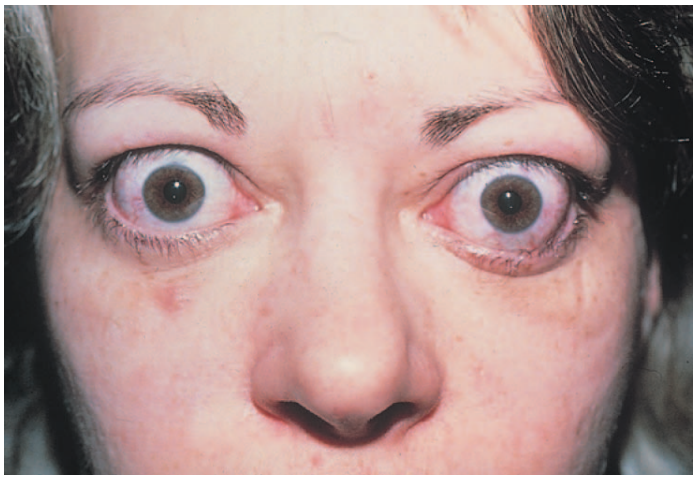
The autonomic nervous system controls smooth muscle and cardiac muscle, both of which are active in the basal state. The hypothalamus also regulates the thyroid gland, another key element in the control of metabolism. With increasing thyroid secretions, the basal metabolic rate increases.

Many factors temporarily or permanently increase the rate of metabolism, including stress, fever, a hot or cold environment, and body type (being tall and thin tends to increase metabolic rates). Conversely, fasting or malnutrition causes the body to compensate by slowing metabolism to save energy.

Because aerobic respiration supplies the metabolic energy expended during the basal state, the most accurate way to determine BMR is to measure oxygen consumption and carbon dioxide production. The Internet offers BMR calculators based on height, weight, age, and gender. These calculators have to be used with caution, because body composition and genetics also affect basal metabolism. Most people who are curious about their BMR probably want to design a diet for losing weight. For that purpose, calorie counters may be more helpful than BMR calculators, because they tend to estimate your real-world calorie expenditures. Also, because many people find it easier to increase activity than to reduce food intake, activity may be more relevant to the campaign to lose weight.

Exophthalmos • Figure 17.9

If left untreated, exophthalmos can cause the eyelids to remain open during sleep, sometimes causing corneal damage.



Hypothyroidism occurs when the thyroid secretes too little T3 and T4. Congenital hypothyroidism occurs from birth and can lead to mental retardation and stunted bone growth unless treated immediately. Myxedema results when the thyroid works normally at birth but fails to secrete enough hormones in adult life, causing slow heart rate, low body temperature, dry hair and skin, muscular weakness, general tiredness, and a tendency to gain weight. This condition is more prevalent in females than males. Oral hormone replacement can treat either form of hypothyroidism.

Hyperthyroidism is the oversecretion of thyroid hormones. Hyperthyroidism, the opposite of hypothyroidism, is the oversecretion of thyroid hormones. The metabolic rate can be 60 to 100% above normal. Exophthalmos, fluid buildup behind the eyes, may cause the eyes to "pop" from their sockets and make the whites of the eyes visible all around the iris, as seen in Figure 17.9. Graves disease, another common hyperthyroid disease, again occurs more often in females than in males. Graves disease may be treated with surgical removal of part of the thyroid or the application of radioactive iodine to the thyroid. As the gland absorbs the iodine, some of its tissue dies, which reduces its output.

T3 and T4 require three and four atoms of iodine respectively, to complete their production. When iodine is scanty in the diet, the precursors to T3 and T4 cannot be converted to completed hormones, so they are held in the thyroid. TSH is continually produced by the anterior pituitary gland because thyroid hormone levels cannot rise in the blood, so there is no negative feedback shut-off for TSH production. The continual production of TSH causes the thyroid to enlarge enough to appear visible on the surface of the larynx, a condition called **goiter**, as seen in Figure 17.10. Goiter can be prevented by simply adding iodine to the diet, so T3 and T4 formation can be completed. Seawater contains iodine, so when waves crash against the shore iodine is aerated with the spray. Inhaling this iodized sea air is sufficient to maintain healthy thyroid functioning for people living near a coast. In the central United States, goiter is prevented by adding iodine to table salt. In a supermarket, you can buy plain salt (NaCl) or iodized salt for the same price. The government subsidizes the addition of iodine so people living inland will not develop goiter.

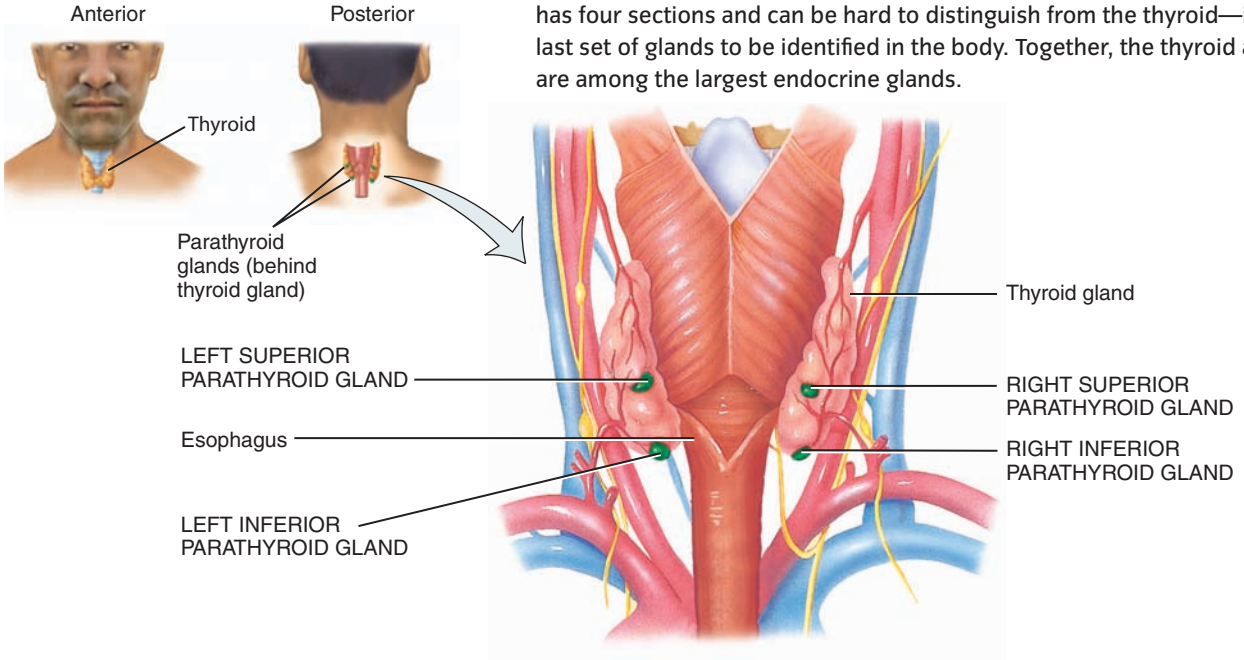
The thyroid also plays a role in calcium regulation. Thyroid cells not involved in producing T3 or T4 produce calcitonin. This hormone stimulates calcium uptake by osteoblasts, putting "calcium in" the bones, as the name suggests. Calcitonin also inhibits osteoclasts, preventing bone from being destroyed. In short, calcitonin causes increased bone mass. The feedback control on calcitonin is simple. When

Goiter • Figure 17.10

Goiter remains a problem in areas where the soil is lacking in iodine and little or no iodine supplements are added to table salt. India, central Africa, and central Asia still struggle with goiter.

Thyroid and parathyroid glands • Figure 17.11

The thyroid gland consists of two lobes lying against the trachea. The parathyroid has four sections and can be hard to distinguish from the thyroid—indeed, it was the last set of glands to be identified in the body. Together, the thyroid and parathyroid are among the largest endocrine glands.



blood calcium is high, calcitonin is produced. When the blood calcium level drops dangerously low, calcitonin is inhibited. The thyroid gland is shown in **Figure 17.11**, with the next set of glands we will consider—the parathyroid glands. See *What a Scientist Sees: Anti-Aging Products: Help or Hoax?* for further discussion of calcium controls.

WHAT A SCIENTIST SEES

Anti-Aging Products: Help or Hoax?

As this image demonstrates, we expect our aging family members to visibly shrink in stature and to be "frail." It is commonly accepted that older individuals have more difficulty with falls, and often will break bones in what seems to be a minor accident. As an example, hip replacement surgery is far more common in the elderly than in the young. As we age, our bones weaken. This weakening is due in large part to an imbalance in the hormones that maintain normal bone density. The osteoclasts are triggered to break down bone, but the osteoblasts are not stimulated to replace that bone to the same degree. Consequently, calcium is removed from the bone matrix but not replaced. In females, this loss is compounded by the fact that as estrogen levels drop during menopause, osteoclast activity is enchanced. Before menopause, the higher estrogen levels suppress osteoclast functioning.

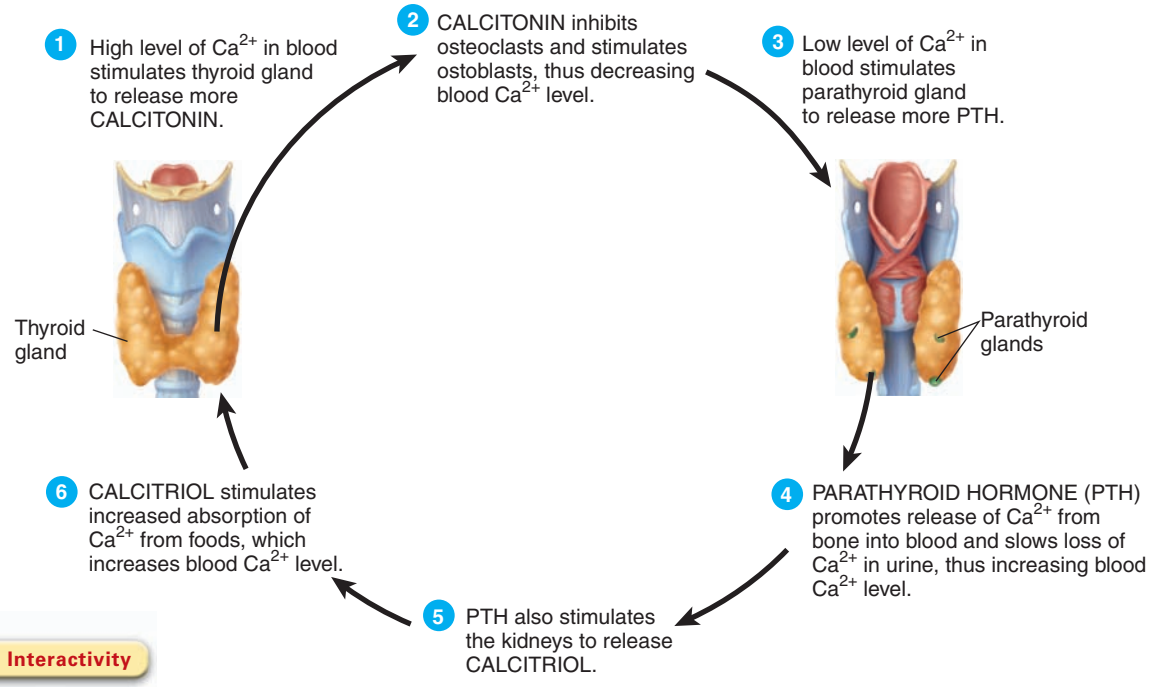
Think Critically

1. What hormone is responsible for triggering the movement of calcium from blood to bone? Can this hormone be regulated externally via injections and monitoring, as is done for insulin levels in diabetics?
2. Why does osteoporosis affect older women more often than men?
3. What benefits are offered for a post-menopausal female on hormone replacement therapy?

PROCESS DIAGRAM

THE PLANNER

Controlling calcium levels in the blood • Figure 17.12



WILEY PLUS Interactivity

The Parathyroid Glands Also Control Blood Calcium

The parathyroid glands, seen in Figure 17.11, secrete a second, and perhaps more important, hormonal control on blood calcium, called parathyroid hormone (PTH). PTH removes calcium and phosphate from bones, stimulates uptake of calcium from the digestive tract, and prevents loss of calcium in the kidneys (where calcium is exchanged for phosphate). This hormone is present throughout life and is the major force in maintaining blood calcium levels in adults. See **Figure 17.12**, showing how calcium levels in the blood are controlled.

The digestive tract cannot absorb calcium simply by interacting with PTH. PTH instead stimulates kidney cells to convert inactive vitamin D in the blood to its active form, which cells in the small intestine use to absorb calcium. Without vitamin D, no calcium can be absorbed. This interaction helps explain why we fortify calcium-rich milk with vitamin D. Doing so supplies the extra vitamin D right when it is needed, helping us absorb more calcium from the milk.

As with calcitonin, the trigger for PTH secretion is the blood calcium level. When blood calcium is low, PTH is produced. When blood calcium is high, PTH is inhibited.

Like the other hormones we have studied, parathyroid hormone is susceptible to hyposecretion and hypersecretion. When too little parathyroid hormone is in the blood (hypoparathyroidism), blood calcium drops precipitously. This drop, in turn, causes nerves to depolarize and muscle cells to begin contracting, resulting in twitches, spasms, and tetany (continuous contraction). With elevated PTH, blood calcium rises and the bones are robbed of calcium, making them soft and prone to damage. High blood calcium leads to the formation of kidney stones. Less obviously, it also causes personality changes and fatigue.

The Thymus and Pineal Glands Are Most Active in Infants and Children

The thymus is a minor endocrine gland in adults but an important one during infancy and childhood. This gland, located in the anterior **mediastinum**, secretes two hormones important in lymphatic cell maturation: thymosin and thymopoietin. As we age, the thymus convolutes, becoming smaller, more wrinkled, and less functional. By adulthood, the thymus can be removed with no noticeable change in health. By age 60, the thymus functions at a mere 10% of its original rate. As mentioned earlier, this decline in thymic function compromises the overall functioning of your immune system.

The pineal gland, like the thymus, is also more active in childhood and infancy. This small "brain pea" lies in the roof of the third ventricle and secretes the hormone melatonin. (Review Figure 17.1.) Pineal-gland cells are indirectly sensitive to light as they react to nerve impulses carried on the adjacent optic nerve. This odd interaction causes some to believe the pineal gland is the remnant of a third eye! Regardless, the pineal gland seems to be involved in sleep patterns and **circadian rhythms**.

circadian rhythm
A daily predictable physiologic cycle based on a 24-hour day.

The pineal gland times its secretion of melatonin by monitoring the optic nerve. Melatonin is secreted only at night, when the optic nerve is quiet. During childhood, melatonin production is tremendously high, but the level drops to a low that usually correlates with the onset of puberty. Is this the elusive trigger that initiates puberty? We cannot be sure, but evidence seems to indicate some involvement.

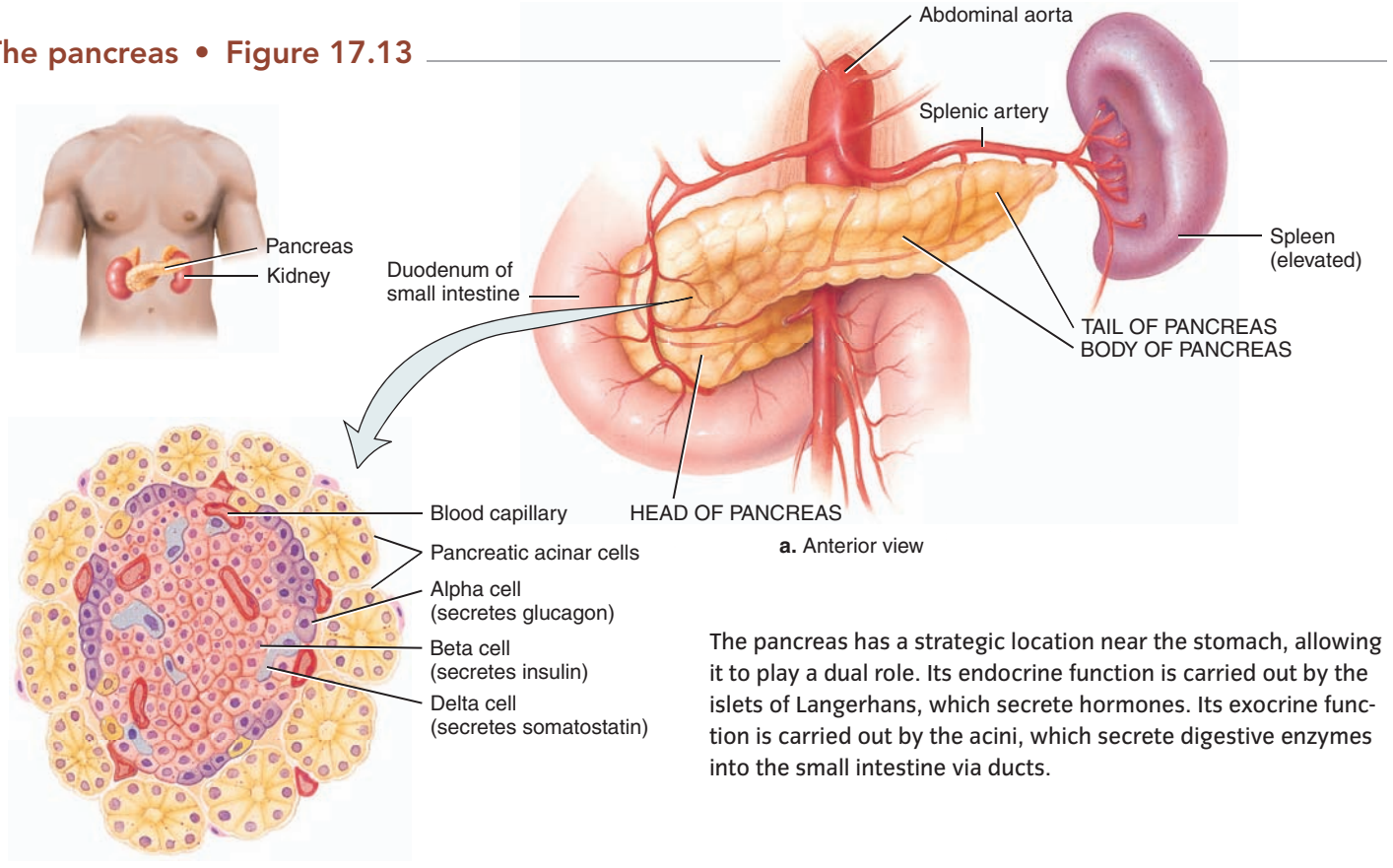
Melatonin may also induce deeper sleep, as it is produced in infants and children while they sleep. The saying "sleeps like a baby" may have a physiological basis. Because of its apparent role in deep sleep, over-the-counter melatonin is marketed as a sleep aid. We really don't understand the mechanism of this hormone. Does melatonin somehow reduce the levels of FSH or LH? Does it help you sleep as advertised? These are interesting questions, and they require more research.

The Pancreas Is Both an Endocrine and an Exocrine Gland

The pancreas plays a dual role: It serves as an exocrine gland that secretes digestive enzymes through ducts and also as an endocrine gland that secretes a number of endocrine hormones involved in maintaining blood glucose levels. Embedded within the exocrine structures of the pancreas are specialized clusters of cells called the islets of Langerhans, which secrete hormones directly into the blood. The pancreas is shown in **Figure 17.13**.

The islets include alpha, beta, and delta cells. The alpha cells secrete **glucagon** when blood glucose levels are low (the name, which sounds like "glucose gone," suggests the function). Glucagon stimulates liver cells to break down stores of glycogen, releasing glucose into the blood. It also causes the breakdown of glycogen in muscle and the production of glucose from amino acids. Glucagon increases blood sugar between meals, supplying energy to the brain and active muscles.

The pancreas • Figure 17.13



The pancreas has a strategic location near the stomach, allowing it to play a dual role. Its endocrine function is carried out by the islets of Langerhans, which secrete hormones. Its exocrine function is carried out by the acini, which secrete digestive enzymes into the small intestine via ducts.

Beta cells of the pancreatic islets secrete **insulin**, a hormone that opposes glucagon. Insulin lowers blood sugar by stimulating liver, muscle, and fat cells to take up glucose. It is the hormone responsible for clearing from the blood all the glucose you get from a meal. If insulin fails, blood glucose levels will rise, causing osmotic balance problems in all tissues. Lack of proper insulin functioning is easily detected by finding sugar in the urine, which immediately suggests the presence of diabetes. Figure 17.14 diagrams blood glucose regulation.

The delta cells of the islets of Langerhans secrete the hormone somatostatin. This hormone seems to inhibit the production of insulin, glucagon, hGH, and a host of other hormones from other glands. The receptors for this hormone are coupled to G-proteins inside the target cells. When somatostatin binds to these receptors, it prevents further processing of hormones through G-protein/cAMP second messengers.

Diabetes mellitus, or simply diabetes, is a common and serious impairment of glucose homeostasis. In essence, the body loses control of the level of glucose in the blood. Diabetes may be the most serious chronic disease in the United States, accounting for at least $174 billion a year in healthcare costs. Over 7% of the U.S. population has diabetes, including 5.7 million people who are unaware that they have the disease. Diabetes is the seventh leading cause of death in the United States, directly or indirectly causing about 234,000 deaths per year.

Diabetes mellitus centers on insulin, the hormone that allows glucose to leave the blood and enter cells. Diagnosis of diabetes is based on observations of **hyperglycemia** (high blood glucose) on at least two occasions. A high level of blood glucose is itself a problem because it means that body cells cannot absorb and utilize the energy they need. In addition, chronic hyperglycemia damages the kidneys, eyes, nerves, heart, and blood vessels.

There are two types of diabetes:

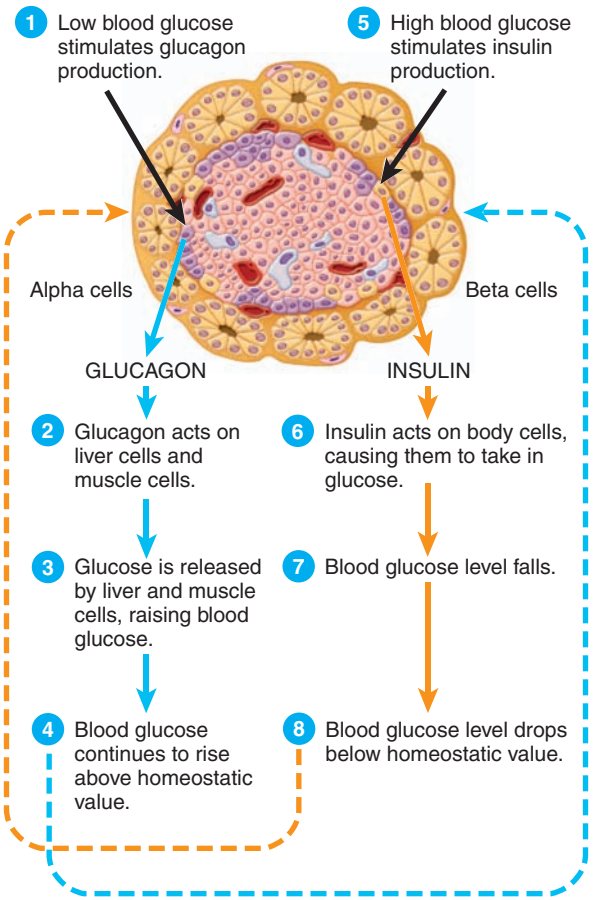
- **Type 1:** This type usually appears before age 25, when the pancreas suddenly stops making functional insulin. Type 1 diabetes used to be called "juvenile diabetes" because of its early onset. An **autoimmune** attack destroys islet cells, rendering the patient unable to make insulin. When type 1 diabetes strikes, the patient must take over the normal responsibilities of the pancreatic islets, monitoring the level of glucose in the blood and injecting insulin when it climbs.

autoimmune Type of immune response launched against healthy tissues, destroying normal organs.

- **Type 2:** This type usually appears during adulthood. The patient has some insulin but maintains an excessive level of blood glucose. Type 2 diabetes, once called "adult-onset diabetes," accounts for at least 90% of all cases. For some reason, cells cease responding to insulin, a phenomenon called *insulin resistance*. In some cases, the beta cells also fail to produce enough insulin. Even if the blood contains an abnormally high level of insulin, the cells still cannot absorb glucose properly. Type 2 diabetes seems to combine genetic and behavioral components, since it is strongly associated with a family history of diabetes, older age, obesity, and lack of exercise. It is more common in women, especially

Regulation of blood glucose via pancreatic hormones • Figure 17.14

The interaction between insulin, glucagon, and blood glucose levels is clearly depicted in this diagram. As blood glucose levels increase, insulin production is stimulated. Cells of the body pick up blood glucose in response to insulin. When blood glucose levels reach a low, glucagon is released to restore the higher blood glucose level.



those with a history of gestational diabetes (diabetes during pregnancy), and among Hispanic, Native American, and African American populations.

Insufficient glucose inside the cells is only one of the problems caused by diabetes. It is not completely clear why one defect, high blood glucose levels, causes such wide-ranging and serious complications, but a large part of the reason is that high blood glucose damages small blood vessels. Diabetes can harm the cardiovascular system: Rates of death from heart attack or stroke are much higher than average rates for the general population. Moreover, impaired blood circulation may force amputations. Diabetes can also cause damage to the eyes (fine blood vessels in the retina leak, causing a type of blindness called diabetic retinopathy), the nerves, and the kidneys.

At present, no one knows how to prevent type 1 diabetes, although researchers are actively investigating how to block the immune attack on the islet cells. Type 2 is a different story. If you have a family history of diabetes and are overweight and/or sedentary, you may have "prediabetes," an elevated level of blood glucose that is not yet high enough to signify true diabetes. Individuals at high risk for diabetes can control their blood glucose levels through diet and exercise, reducing their body's exposure to the toxicity of high blood glucose and slowing the onset of diabetes.

The key first step in treating diabetes is to control blood glucose through a combination of insulin, other medications, diet, exercise, and close monitoring of blood glucose levels. Insulin may be injected or supplied through a pump implanted beneath the skin. **Figure 17.15** shows a woman controlling her diabetes. A form of inhalable insulin is under consideration as a treatment in the future.

Type 2 diabetes, once considered an adult-onset disease, is now appearing in younger people, apparently as a result of unhealthy diet and lack of activity. Higher rates of type 2 diabetes are an unfortunate outcome of the obesity epidemic in the United States. Unlike type 1 diabetes, type 2 can often be controlled by changing diet and lifestyle—for example, by eating smaller portions and increasing exercise.

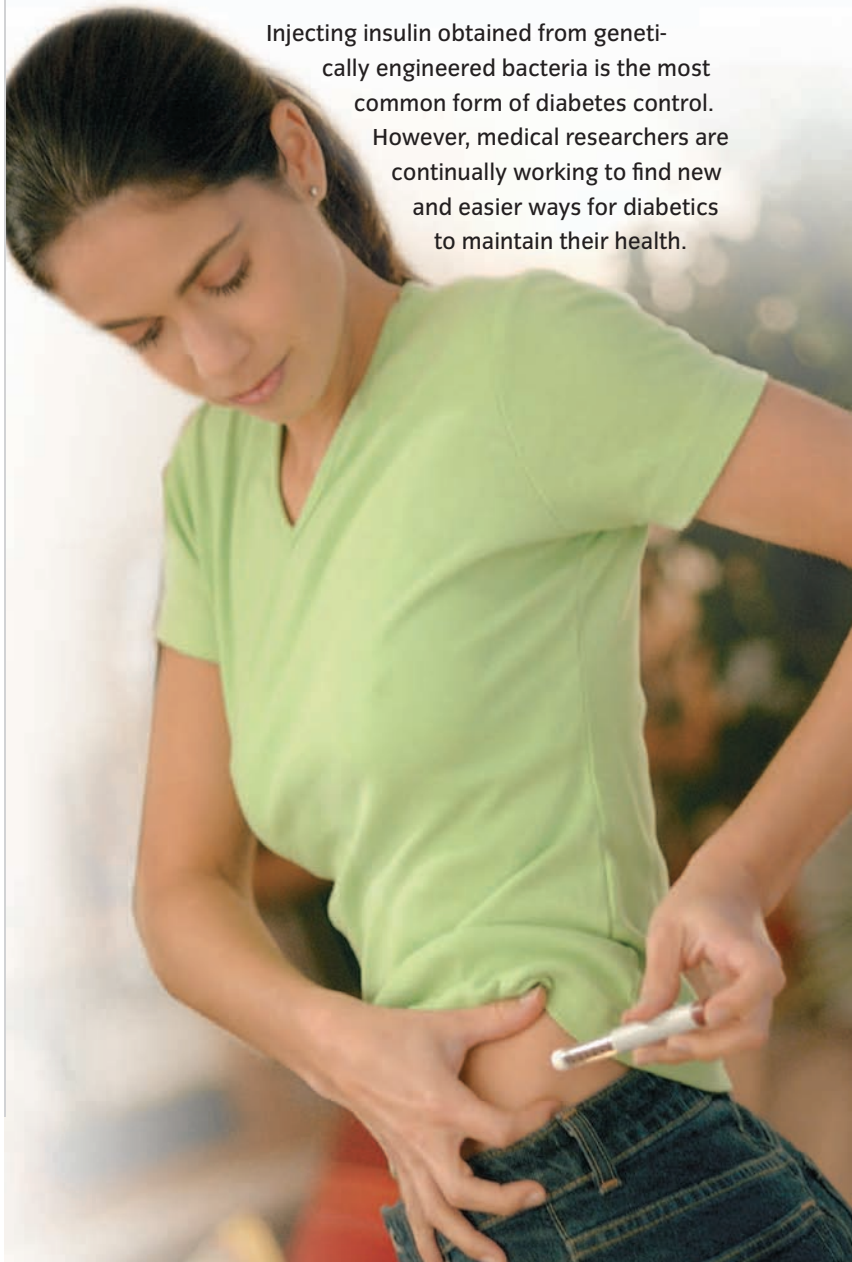
Other Organs Have Endocrine Functions

Although they are not specifically endocrine organs, the kidney, heart, and several digestive organs also secrete hormones. The **kidney** secretes erythropoietin, calcitriol, and renin. As you learned in Chapter 12, erythropoietin stimulates the production of red blood cells, thereby increasing blood volume and blood pressure. Calcitriol is involved in calcium ion homeostasis by stimulating the absorption of calcium and phosphate along the digestive tract. Like erythropoietin, renin is involved in blood pressure and blood volume. When renal blood flow declines, the kidney cells secrete renin. This hormone begins an enzymatic chain that ends with the secretion of aldosterone, an increase in thirst, and water retention. As a result, blood volume increases, renal blood flow increases, and in typical negative feedback style, the stimulus for renin secretion is removed.

The heart and intestines also secrete hormones.

Specialized cells in the atria of the heart secrete atrial natriuretic peptide (ANP) when they are stretched by an increase in atrial blood volume. ANP functions the opposite of renin: Water is lost to the urine, thirst is suppressed, and blood volume decreases.

Controlling diabetes • Figure 17.15



Injecting insulin obtained from genetically engineered bacteria is the most common form of diabetes control. However, medical researchers are continually working to find new and easier ways for diabetics to maintain their health.

The intestines produce hormones that coordinate the activity of other digestive organs, including gastrin, cholecystokinin, and secretin. Gastrin stimulates stomach secretions. Cholecystokinin causes the release of bile. Secretin initiates the exocrine functions of the pancreas, causing the pancreas to secrete digestive enzymes into the duodenum.

Local hormones stay close to home. There is another type of hormone that can be produced by just about any cell of the body. This type is called a local hormone, or paracrine. Paracrines are chemical compounds produced by one cell and released into the local environment, so they affect only surrounding cells. Histamines and prostaglandins are examples of paracrine secretions. Both of these secretions cause localized inflammation and fluid leakage, but they become inactive just a short distance from their point of secretion.

CONCEPT CHECK STOP

1. **What** are the major endocrine glands and their associated hormones?
2. **What** are the hormones of the anterior and posterior pituitary glands, and **what** are their functions?

17.3 Development Takes Us from Infancy to Adulthood

LEARNING OBJECTIVES

1. **Describe** the stages of life.
2. **Relate** the events of development to the activity of the endocrine system.

Growth and maintenance of the body require the proper functioning of the endocrine glands. Hormones from these glands direct our sequential growth and maturation from the neonatal period and infancy through childhood, adolescence, and adulthood. Even **senescence**, or aging, has hormonal controls.

The Newborn Baby and Infant Are Dependent Beings

The baby's first month is a time of dependency. The body systems are functioning on their own, but some are not yet fully functional. Have you ever held a newborn? Then you probably noticed that the head bobbed and jerked around if you did not support it. Maybe the hands and feet waved at random. Although the brain is formed, many connections remain to be developed or are not yet functioning well. Neurons will continue to be added for a few more years, and connections will be formed and re-formed throughout a lifetime. Memories cannot yet be formed, hearing is less acute than it will become, and muscular control is primitive. **Neonates** (**Figure 17.16**) spend most of their first month suckling, sleeping, urinating, and defecating. Even the digestive system is immature, not able to handle solid foods. The proportions of the head, limbs, and torso are much different from those of an adult, with the head as long as the torso. Rapid growth of torso and limbs will occur in good time.

neonate The newborn child, from immediately after birth to approximately one month of age.

Neonate • Figure 17.16

This newborn baby exhibits typical neonatal behavior—sleeping comfortably in Dad's arms!

Infancy is a time of rapid development. From month 2 through month 15, body systems mature, control improves, and body proportions begin to shift, as shown in Figure 17.17. By the end of infancy, the head is one-third of the body length, and the limbs are lengthening. The amount of muscle tissue increases rapidly, and the brain grows quickly. Half of all **postnatal** brain development occurs in this period. The cerebral cortex expands, adding areas associated with motor functioning, speech, and sensory perception. The skeleton continues to harden, and ossification of the skull is almost complete. Teeth erupt, and solid foods can be eaten. Coordination rapidly improves, so that by 14 months, most infants have mastered the complex muscular patterns of walking. Their personality continues to develop, and they can generate laughter among observers as they explore their world.

postnatal After birth.

The immune system is notably slower to mature. Many vaccinations are ineffective in infants because they cannot yet manufacture antibodies to the antigens. Vaccination regimes start with small doses, and boosters are administered to continually challenge the developing system.

Childhood and Puberty Are Times of Almost Steady Growth

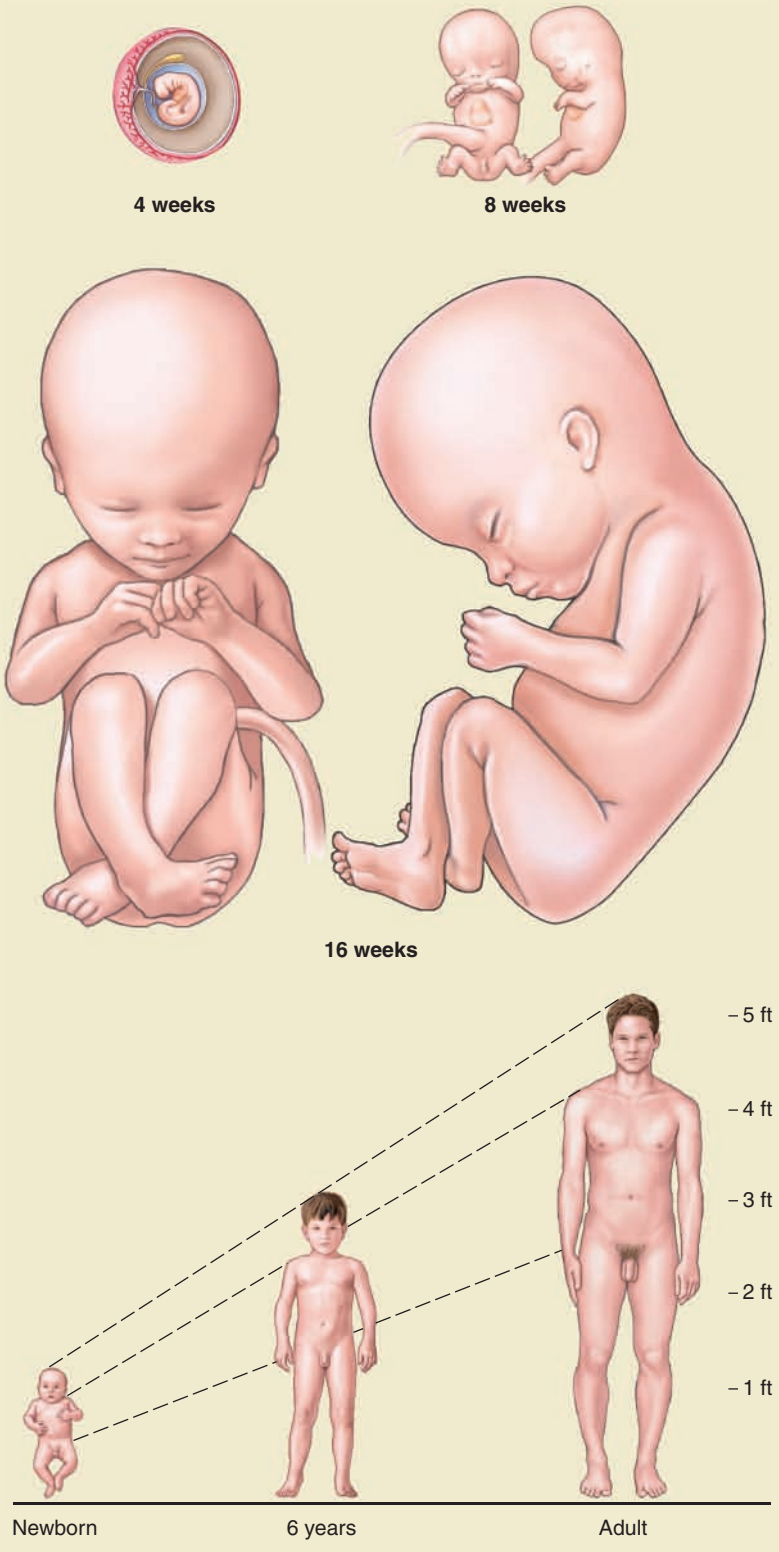
Childhood is much longer than infancy. From age 2 until approximately age 12, the body and all systems grow. The brain will reach 95% of its size by the time puberty ends childhood. Coordination improves, muscles and bones continue to grow, muscular strength increases, and weight is added. By the end of childhood, the average human (male or female) weighs 45.4 kilograms (100 pounds). The long bones lengthen, adding height as well as reach. Adult proportion is attained, with the torso and limbs now approximately equal in length and the head a mere one-eighth of the total body length. All systems are functioning, except the reproductive system.

Growth is regulated by hormones. The regular, sequential changes everyone experiences during their childhood years are governed by hormones. Through the end of childhood, the endocrine system has been directing the patterned growth of bones, muscles, and nervous tissue. The endocrine system has also been working to maintain a healthy metabolic rate, monitor sleep patterns, maintain ion and water balance, and regulate blood levels of calcium

Development chart showing body proportions • Figure 17.17

Note the change in relative length of the head and body with time.

WILEY PLUS Video



and glucose. When puberty begins, the endocrine system will also stimulate the appearance of secondary sexual characteristics and the production of eggs or sperm.

Puberty brings the ability to reproduce. From the neonatal stage through childhood, all of the endocrine glands discussed above have been functioning. By the end of childhood, the thymus is slowing its production of thymosin, and the pineal gland is shutting down melatonin production. Between ages 12 and 17, a final growth spurt occurs. Human growth hormone surges through the system, causing a rapid and obvious increase in size of the muscular and skeletal systems. This increase can be so rapid that adolescents often suffer a temporary loss of coordination. The internal organs also grow: The lungs, stomach, and kidneys double in size, and the brain increases by approximately 5%.

During puberty, which occurs near the time of this growth spurt, the reproductive organs begin to function. This functioning is directed by the production of gonadotropin-releasing hormone (GnRH) from the hypothalamus. GnRH causes the release of FSH and LH by the anterior pituitary gland. In females, the ovaries respond by maturing egg follicles (recall that FSH stands for follicle-stimulating hormone) and producing estrogen. Secondary sex characteristics appear as estrogen levels increase. Males begin to produce sperm and testosterone due to FSH and LH, respectively. Puberty is defined as the onset of the menstrual cycle in females (menarche) and the appearance of nocturnal emissions in males.

Adulthood Is Usually the Longest Stage

After puberty is reached, adulthood begins (see **Figure 17.18**). This is a long stage, lasting from approximately age 15 to 18 until death. The average life expectancy of Americans at birth is now 77.6 years. Women live about five years longer than men. During this period, adults first see an improvement in overall health but then start to lose some of their physical prowess. The timing of aging varies with individuals, but the pattern is similar. Adults are at their physiological peak in their early 20s. Assuming that they lead a healthy lifestyle and avoid serious illness, the peak performance of the 20s can be maintained for almost 20 years. By age 40, however, symptoms of aging begin to appear, as seen in **Table 17.4**. Even the most athletic and well-trained adult notices a slight loss in athletic performance by the late 40s. As we move past 50, predictable age-related changes arrive. Eventually, eyesight weakens, hearing becomes less acute, muscles lose strength, and bones often become brittle. A good diet and a regular exercise routine help slow the process but do not stop it. In the female, menopause is another indication of aging.

Stages of life • Figure 17.18

Childhood is defined as that time between birth and puberty. After puberty, the stages of adulthood include the teen years, early adulthood (or middle age), and old age. Each of these stages are illustrated below.

The effects of aging on the organ systems Table 17.4

System	Changes associated with aging
Integumentary system	1. The epidermis thins and weakens. 2. The immune cells of the skin diminish. 3. Vitamin D production decreases by up to 75%. 4. Melanocyte production decreases and the skin becomes paler. Blood supply to the skin is reduced, and sweat glands become less active. 5. Hair production slows, and hairs become thinner and less colorful. 6. The dermis weakens and wrinkles develop. 7. Secondary sex characteristics diminish, and fat deposition becomes similar in males and females.
Lymphatic system	1. The entire immune system becomes less effective. 2. T cells become less responsive, and their numbers drop. 3. B cell populations become less responsive. 4. The chance of developing cancer increases, as does the susceptibility to viruses.
Skeletal system	1. The bones become thinner and weaker. 2. Epiphyses, vertebrae, and the jaw lose mass, resulting in shorter stature and tooth loss. 3. Bones become fragile, and limbs are more susceptible to breaking from simple actions like standing or walking.
Muscular system	1. Skeletal muscle fibers become smaller in diameter and therefore lose strength and endurance. 2. Skeletal muscle becomes less elastic and less flexible. 3. Exercise becomes difficult as fatigue comes more rapidly. 4. Recovery from muscular injuries slows.
Nervous system	1. The brain is reduced in size and weight as the cerebral cortex shrinks. 2. The number of neurons decreases. 3. Blood flow to the brain declines. 4. Synaptic connections in the brain decrease, and neurotransmitter production declines. 5. Abnormal deposits and tangles may appear in neurons.
Cardiovascular system	1. Blood hematocrit decreases; embolism and venous pooling are more likely. 2. Cardiac output drops. 3. Heart muscle becomes less elastic and responsive to bodily demands. 4. Scar tissue may build up in the heart. 5. Arterial walls lose elasticity. 6. Plaques and calcium deposits in vessels become more common.
Respiratory system	1. Elastic tissue in the system deteriorates. 2. Chest movements become more difficult as joints become less flexible. 3. Respiratory membrane is lost due to lifelong abrasions.
Digestive system	1. The digestive epithelium is less able to regenerate, becoming more susceptible to disease and tearing. 2. Smooth muscle tone throughout the tract decreases, slowing the clearance of material. 3. Areas that were slightly compromised early in life are now overwhelmed by a lifelong accumulation of damage.
Urinary system	1. The number of functional nephrons declines. 2. Glomerular filtration decreases. 3. ADH sensitivity diminishes, increasing the chance of dehydration. 4. Control over the external urinary sphincter is compromised, leading to incontinence.
Endocrine systems	1. Reproductive hormone production declines. 2. The thymus shrinks, dramatically decreasing production of thymosin.
Reproductive systems	1. Menopause causes the cessation of the female reproductive cycle; hormone levels drop, follicles no longer respond to FSH, and unpleasant symptoms may occur. 2. The male climacteric occurs, reducing circulating testosterone levels.

See *Health, Wellness, and Disease: Ah, to Be Young Again…* for a discussion of anti-aging products.

Today, three lines of thought are most often offered to explain aging: limits on cellular division, accumulated cellular damage, or the demise of organ systems.

Normal (noncancerous) cells can only go through a certain number of **cell divisions** or a predetermined number of mitotic rounds. On the ends of each chromosome are strands of DNA that do not code for proteins, called telomeres. With each mitotic division, the telomeres get shorter, so it appears that telomere length may regulate the number of possible generations. Most tissue cells in the laboratory live for only 50 to 80 generations before they die out or become **senescent**. Cancer cells are an exception, as they can produce thousands of generations. Cancer cells produce the enzyme telomerase to rebuild shortened telomeres, which may explain their immortality.

Cellular damage refers to damage to DNA. We have repair mechanisms to fix strands of DNA that have suffered various degrees of damage. However, our metabolism produces **free radicals** and other noxious compounds that damage DNA, and some lifestyles cause further damage. If the damage overwhelms the repair mechanisms, the cell will die, and this is, according to one theory, a cause of aging. In the laboratory, putting animals on a restricted-calorie diet prolongs life. This may be due to a slightly lower body temperature that develops as a result of less energy usage. Lower temperatures slow enzymatic reactions, thereby slowing the internal damage caused by the by-products of these reactions. Few people are willing to go on such restricted diets, but many are willing to swallow antioxidants in the hope that they will reduce free radicals and DNA damage, and thereby extend life. Disappointingly, some large studies have found no such benefit from the most popular antioxidant vitamins, including C and E.

senescent At the stage of aging or growing old.

free radicals Highly reactive ions, such as oxygen.

The last theory on aging reminds us that "a chain is only as strong as its weakest link." If one small change occurs in an **organ system**, the repercussions may kill the organism. Many diseases provide evidence for this theory. If cutaneous cells that normally exclude pathogens are weakened by poor diet, viral infection, or physical damage, bacteria may find an "open door" into the body and cause septicemia. Without medical attention, homeostasis is com-

HEALTH, WELLNESS, AND DISEASE

Ah, to Be Young Again . . .

THE PLANNER

. . . Or at least look young! As we age, changes in our appearance are going to happen. Our skin will wrinkle and lose elasticity in many areas. We will lose muscle mass and will experience fatigue far more easily. Our fat deposits will shift, leaving us with flabby arms, larger midsections, and skinny legs. There is an impressive array of products available that claim to prevent or reduce these effects. One area that has undergone a boom in recent years is the anti-wrinkle product line. Wrinkle creams promise to remove the appearance of tiny wrinkles and smooth skin. Some even go so far as to promise to restore younger-looking skin. These serums are smoother than facial creams, and usually include vitamins that are known to reduce free radicals in the cells. But what really works? According to the Mayo Clinic, the following ingredients may truthfully help reduce the appearance of wrinkles if used over a long period of time.

- *Retinol, or vitamin A*. Retinol is a less potent form of vitamin A than is found in the prescription wrinkle cream Tretinoin. It has been proven to clinically reduce wrinkles if used properly, by removing damaging oxygen molecules from skin cells.
- *Hydroxy acids*. These are synthetic versions of natural acids found in fruits. These acids remove the upper layers of dead skin, stimulating production of new, and therefore younger, skin cells.
- *Copper peptides*. Copper peptides are small proteins associated with copper ions. In the laboratory, copper peptides have been shown to aid in wound repair and collagen production, but they have not been proven effective on people with aging skin.
- *Green tea extracts*. These compounds carry antioxidant properties similar to retinol.

Because these creams are non-prescription, it is important to remember that the FDA does not evaluate them. There is no guarantee that they will work at all! The doses of these active ingredients are far lower in over-the-counter products than in their prescription counterparts, rendering them less effective. Also, the benefits of these creams will stop once you stop using the product. They are temporary fixes. If you are serious about reducing wrinkles, you should begin to take precautionary steps early in life. Use sun protection, apply moisturizers liberally, and do not smoke.

ETHICS AND ISSUES

THE PLANNER

Has Your Endocrine System Been Disrupted Today?

Our endocrine systems are very good at what they do: delivering small amounts of specific chemicals to virtually every cell in the body. That same delivery system is also very good at delivering small amounts of toxins to the cells. Indeed, the Centers for Disease Control and Prevention estimates that endocrine disruptors are present in the bodies of about 80% of Americans. Endocrine disruptors are hormone-like chemicals that are used in packaging foods, suppressing weeds and pests on farms, and making plastic flexible, among other uses. We discussed one kind of endocrine disruptor—environmental estrogens—in Chapter 3.

When present in higher-than-normal concentrations, some endocrine disruptors cause reproductive malfunctions and malformations in some animals (both wildlife and lab animals). As yet, however, we do not know precisely what effects they are having on our endocrine systems and *our* bodies.

In 2008, two endocrine disruptors became especially newsworthy:

- Bisphenol A (BPA), used to make plastic more supple, is found in many products, most notably plastic baby bottles and water bottles.
- A group of compounds called phthalates are also used as plastic enhancers and are found in many items, including toys, medical tubing, blood bags, and catheters.

BPA is a hormone impostor—it binds to receptors and causes a response in target cells similar to the response caused by natural hormones. Phthalates are different; they usually function as hormone blockers—they cause no response but block natural sex hormones from binding to receptors. One study found that some women with higher-than-normal concentrations of phthalates give birth to boys with smaller-than-normal genitals, suggesting that the action of natural sex hormones was blocked during pregnancy.

The potential danger of endocrine disruptors has been known for some time, and in 1998 the Environmental Protection Agency announced an Endocrine Disruptor Screening Program. As of 2008, the program was still deciding what kinds of tests to run on which suspected endocrine disruptors. Some believe that industry lobbying groups will keep the program crawling and not running for years to come.

Critical Reasoning Issues Making decisions without extensive and conclusive data is difficult but often necessary. We have to be careful not to jump to conclusions; as one scientist says, if the stork population is declining in an area where human births are also declining, that does not prove that storks bring babies. On the other hand, we must not bury our heads in the sand by ignoring a potentially dangerous situation.

Some researchers think we should apply the "precautionary principle," which holds that if there is reason to suspect that a chemical is causing unwanted effects at a certain dosage in a certain time and place, it should be limited or banned, even if the cause-and-effect mechanism is not well understood and the evidence not definitive. Others believe that the risk from endocrine disruptors is minimal at the dosages we normally receive—that is, our bodies can handle them—and any evidence to the contrary is circumstantial at best.

Think Critically

1. Would you apply the precautionary principle to endocrine disruptors?
2. Research the amount of testing and regulation that the hundreds of new chemicals coming into our environment every year undergo. Are these new chemicals adequately tested and regulated?

promised and, if the bacterial growth remains unchecked, death follows.

Luckily, just as death is inevitable, so is birth. Despite the daunting odds against everything necessary for pregnancy, fertilization, and growth falling into place, the miracle of life continues. Even though our environment can provide some challenges for our endocrine systems—see *Ethics and Issues: Has Your Endocrine System Been Disrupted Today?*—the human body is awe-inspiring, functioning with precision yet tolerance—not merely maintaining homeostasis in the face of incredible odds but in fact thriving.

CONCEPT CHECK STOP

1. **What** are the stages of life and the characteristics of each?
2. **What** hormones are directly involved in the onset of puberty?

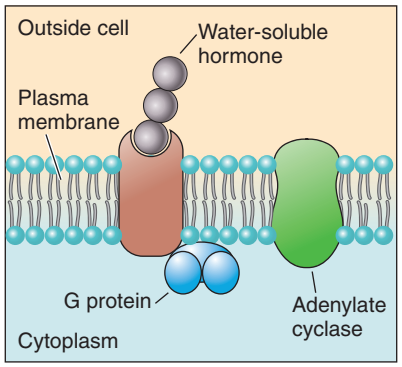
Summary

THE PLANNER

1 Hormones Are Chemical Messengers 456

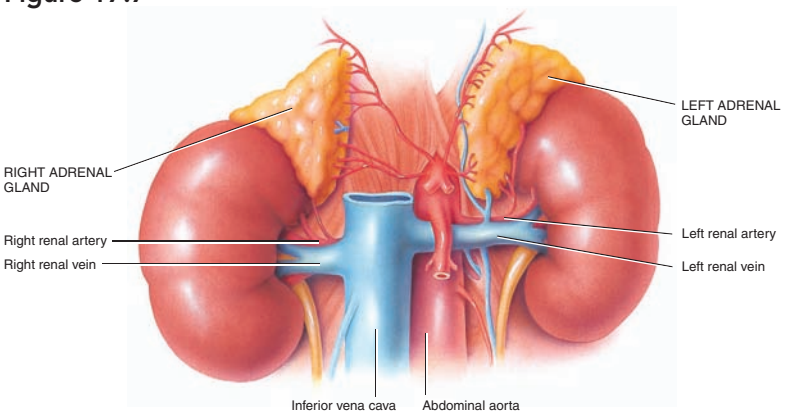
- The endocrine system is responsible for maintaining growth and development. It includes the hypothalamus, pituitary gland, thyroid, parathyroid glands, thymus, pancreas, adrenal glands, and pineal gland.
- Endocrine products, or hormones, communicate with distant target cells.
- Hormones are either lipid-soluble or water-soluble, as shown here. They bind to receptors and alter the functioning of the target cell. Steroid hormones reach receptors within the cell, whereas nonsteroid hormones bind to a membrane receptor. Nonsteroid hormones activate a second messenger inside the cell. They generally act faster than steroid hormones, because nonsteroid hormones alter proteins already present in the cell.

Figure 17.3



- The adrenal glands, shown here, atop the kidneys, secrete a number of hormones. These glands have an outer **cortex** and an inner **medulla**. The cortex secretes glucocorticoids, **mineralocorticoids**, and small amounts of estrogen and testosterone.

Figure 17.7



- The thyroid gland secretes two structurally similar hormones, T3 and T4. These hormones are involved in the basal metabolic rate and help determine how quickly and efficiently you use energy. Calcitonin is also secreted by the thyroid gland.
- The parathyroid glands secrete a second hormonal control on blood calcium, called parathyroid hormone (PTH). PTH removes calcium and phosphate from bones, stimulates uptake of calcium from the digestive tract, and prevents loss of calcium in the kidneys.
- Other glands and organs also secrete important hormones.

2 The Endocrine Glands Secrete Directly into the Bloodstream 461

- The hypothalamus secretes factors that control the pituitary gland, which in turn secretes nine hormones: oxytocin, ADH, hGH, PRL, FSH, LH, MSH, ACTH, and TSH. Most of these hormones are controlled by negative feedback systems. ACTH stimulates the production of steroid hormones from the adrenal glands. TSH causes activation of the thyroid gland. FSH and LH affect the reproductive organs. ADH causes the kidneys to retain water. Oxytocin promotes smooth muscle contractions in the pregnant uterus and in the mammary glands after a baby's birth. MSH may increase the production of melanin. PRL promotes milk production in females; its role in males is not known.

3 Development Takes Us from Infancy to Adulthood 474

- The endocrine system controls the long-term changes observed during growth and development in the neonate, infant, child, adolescent, and adult.
- Puberty marks the shift from child to adult.
- Aging is the progressive slowing of body functions, and while the timing of events differs with individuals, certain events are expected. Visual acuity diminishes, muscle strength is lost, skin thins, reproductive organs slow or stop functioning, bones lose density, and nervous system functioning decreases.

Key Terms

- autoimmune 472
- basal metabolic rate 467
- circadian rhythm 471
- cortex 465
- cortisol-releasing hormone 466
- cyclic AMP (cAMP) 458
- endorphins 461
- enkephalins 461
- free radicals 478
- gonadotropins 463
- kinase 458
- medulla 465
- mineralocorticoids 463
- neonate 474
- postnatal 475
- senescent 478
- somatostatin 459

Critical and Creative Thinking Questions

1. How does the hypothalamus govern the pituitary gland? Compare the route taken by hypothalamic releasing factors to the route taken by hormones that stimulate the anterior pituitary gland. Which route is more direct? Why?
2. Compare the pathologies of type 1 and type 2 diabetes. What is similar in these two disease states?
3. Many hormones are associated with fluid balance. List those hormones covered in the chapter, and describe each of their functions. How do they interact? Try to figure out which ones act together and which inhibit one another.
4. Which hormones are involved in puberty? GnRH is released from the hypothalamus, stimulating the release of the two gonadotropic hormones from the anterior pituitary gland. Which hormones are these? What other hormones are secreted in response to the action of these pituitary hormones? Do any other hormones arise during puberty?
5. **CLINICAL CLICK QUESTION**
   Rob and Julie were excited to move into their new farm in the Midwest. The water on Rob and Julie's farm came from the existing well, dug when the house was built and positioned squarely between the house and the corn and sorghum fields. Rob felt strongly that herbicides were not a good choice, so did not spray them on his fields despite the growth of broadleaf weeds in his corn fields. When Julie became pregnant, they became more concerned about the previous owner's farming practices. To be safe, Rob and Julie took a water sample to a toxicology lab for analysis.

   What type of compounds might they want to test for? Why is it critical that they determine the safety of their drinking water at this time?

   Atrazine was a commonly used herbicide on fallow fields, Christmas tree farms, and on corn, sugarcane, and pineapple crops. After it was released for widespread use, atrazine was found to be slightly to moderately toxic to humans. It remains in water supplies for many years, and causes changes in the brain, heart, liver, and kidneys of experimental animals. As doses increase, toxicity also increases. Atrazine is an endocrine disruptor, interfering with hormone production. It is currently classified as a restricted-use pesticide, available only to certified applicators.

   If there is atrazine in Rob and Julie's well water, how might that effect their developing baby? Is it detrimental to Rob and Julie as well? Look up the effects of atrazine online by visiting http://www.nrdc.org/health/atrazine/ and http://pmep.cce.cornell.edu/profiles/extoxnet/24d-captan/atrazine-ext.html. Develop a plan for these two that will ensure the health of their family, while not causing financial ruin to Rob's budding corn production.

What is happening in this picture?

When a bone is broken, the healing process is often long and uncomfortable. Because the bone cannot support any weight during this period, casts or splints are used. These aids also prevent movement of the two ends of bone while the broken area knits back together. In Chapter 6 we discussed the process of bone repair, including describing the functions of each of the cells involved. Without the endocrine system, however, these cells would not be nearly as efficient in this task.

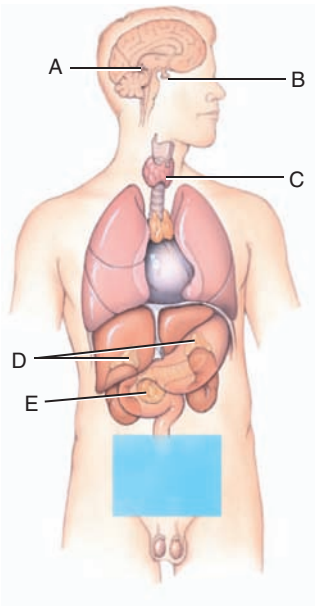
Think Critically

1. Obviously, calcium is required to rebuild the bone matrix. What hormones are necessary to ensure that blood calcium levels remain high enough to allow the osteoblasts to form new bone?
2. As the bone repairs, the muscular and cardiovascular tissue around the break will also repair. What hormones are responsible for the growth and development of body tissues? What glands produce these hormones?
3. Would you expect the pancreas to alter the production of insulin or glucagon during the healing process? Why or why not?
4. How might damage to the anterior pituitary gland affect repair of this individual's bone and surrounding tissue?

Self-Test

1. The functions of the endocrine system include _____.
   a. cellular communication
   b. precise timing of development
   c. maintaining fluid balance
   d. All of the above are correct.

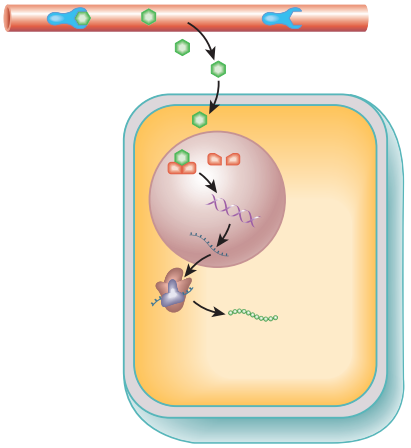
Questions 2 and 3 relate to this diagram.



2. The letter A in the figure indicates the _____.
   a. adrenal glands
   b. pancreas
   c. pineal gland
   d. pituitary gland

3. In the preceding figure, the endocrine gland that secretes both insulin and glucagon is labeled as _____.
   a. A
   b. B
   c. C
   d. D
   e. E

4. The figure shown below demonstrates the action of _____.
   a. steroid hormones
   b. nonsteroid hormones
   c. ADH
   d. thyroid hormones



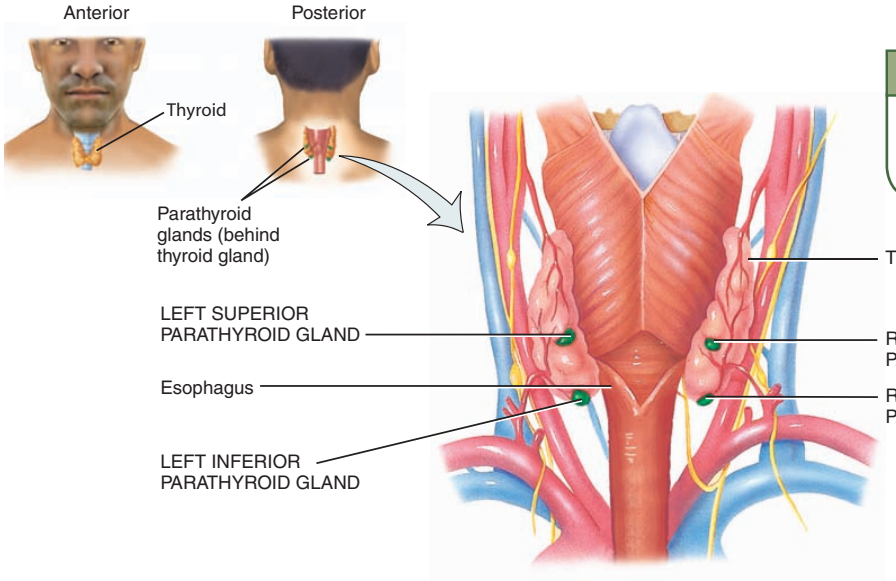
5. The posterior pituitary gland secretes _____.
   a. human growth hormone
   b. hypothalamic releasing factors
   c. oxytocin
   d. ACTH

6. The individual shown in the photo below shows the signs of _____.
   a. overproduction of one specific pituitary hormone
   b. underproduction of the adrenal hormones
   c. overproduction of thyroid hormones
   d. underproduction of gonadotropic hormones

7. The hormones produced from the adrenal cortex include ____.
   a. glucocorticoids
   b. glucagon
   c. human growth hormone
   d. endorphins

8. _____ is an example of an autoimmune disease of the endocrine glands.
   a. Cushing's disease
   b. Addison's disease
   c. Diabetes insipidus
   d. Goiter

9. The two endocrine glands shown in the illustration below both regulate _____.
   a. blood glucose levels
   b. metabolic rate
   c. production of estrogen and testosterone
   d. blood calcium levels



10. The endocrine gland that serves as an internal biological clock is the _____.
    a. pineal gland
    b. pituitary gland
    c. thymus
    d. thyroid

11. The organ that serves as an endocrine gland and secretes erythropoietin, calcitriol, and renin is the _____.
    a. stomach
    b. pancreas
    c. brain
    d. kidney

12. The hormone secreted by the atria of the heart is involved in _____.
    a. the production of red blood cells
    b. digestion
    c. maintaining blood volume
    d. absorbing calcium

13. The correct term for the stage of life of this baby is _____.
    a. fetus
    b. neonate
    c. infant
    d. adolescent

14. The brain grows most quickly during _____.
    a. the neonatal period
    b. adulthood
    c. infancy
    d. senescence

15. The two hormones responsible for the onset of puberty are _____.
    a. FSH and ADH
    b. FSH and LH
    c. LH and ACTH
    d. melatonin and oxytocin

THE PLANNER

Review your Chapter Planner on the chapter opener and check off your completed work.

18 The Reproductive Systems: Maintaining the Species

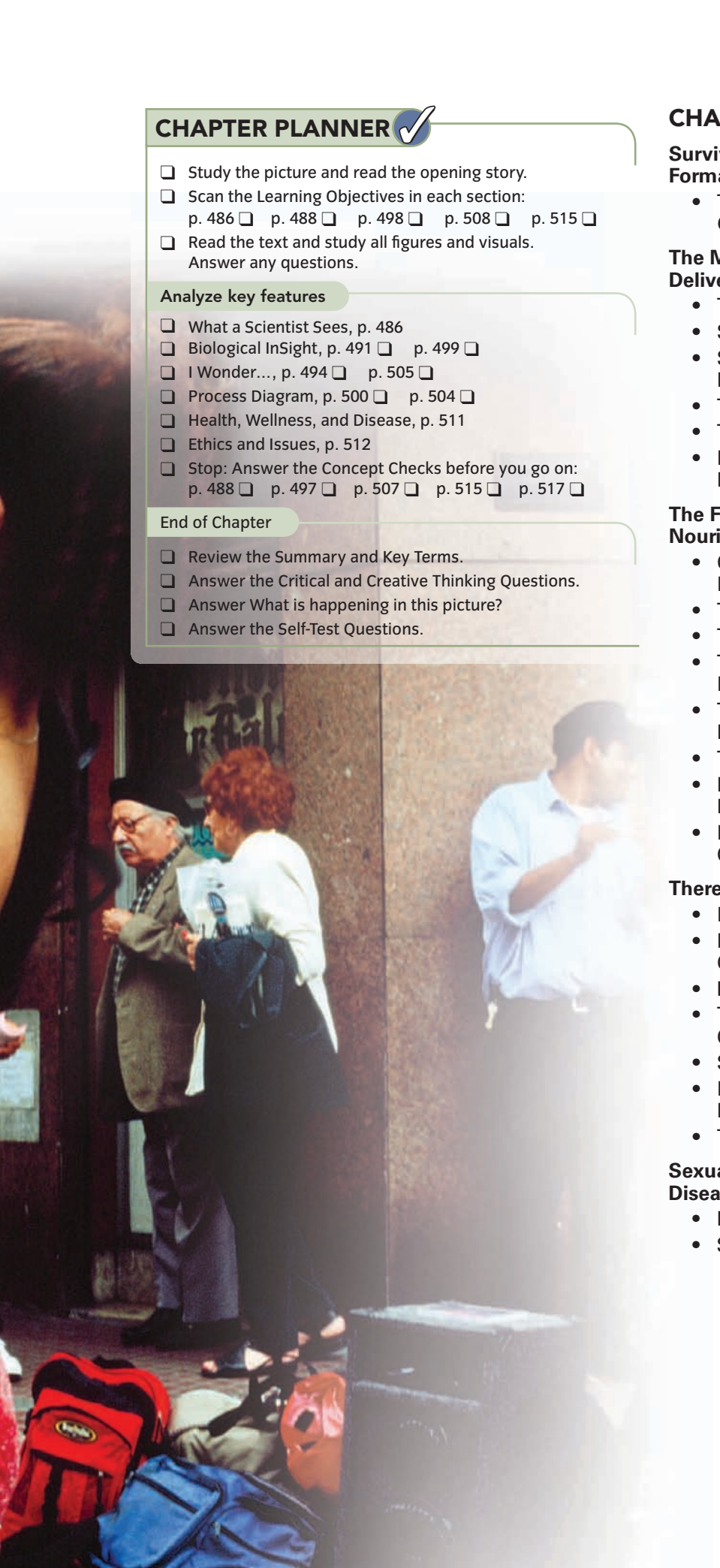
"Birds do it. Bees do it. Even educated fleas do it. Let's do it. Let's fall in love."

Songwriter Cole Porter got it right decades ago, when he wrote this about sex. Okay, we'll admit that what he called "love" is actually "sexual reproduction," but you get the idea. There is nothing new about sex, which plants have been using to ensure reproductive success for many millions of years. The need to join gametes from two individuals traces back to all life-forms from fungi to flowering plants, from birds to bees, and of course to humans.

Sexual reproduction has evolutionary benefits: It speeds up the formation of new genetic configurations that can be tested against the environment. It also dilutes harmful genes.

The urge to engage in sex is one of the strongest human desires, ranking behind only eating and breathing. Many biologists believe that this urge is maintained by the process of evolution through natural selection: Without sex, we do not leave descendants. The genes of people who have sex and reproduce are found in the next generation and, to the extent that reproduction is a genetic urge, the mechanism is self-perpetuating.

Since reproduction is critical to survival of the species, the process needs to be managed. Indeed, many of the most common and important human customs concern reproduction: marriage, childbirth, and family ties. In this chapter, we look at the physiology and anatomy of reproduction, and include some scientifically based suggestions for keeping the urge to reproduce in a healthy framework.



CHAPTER PLANNER

- ❑ Study the picture and read the opening story.
- ❑ Scan the Learning Objectives in each section:
  p. 486 ❑ p. 488 ❑ p. 498 ❑ p. 508 ❑ p. 515 ❑
- ❑ Read the text and study all figures and visuals. Answer any questions.

Analyze key features

- ❑ What a Scientist Sees, p. 486
- ❑ Biological InSight, p. 491 ❑ p. 499 ❑
- ❑ I Wonder..., p. 494 ❑ p. 505 ❑
- ❑ Process Diagram, p. 500 ❑ p. 504 ❑
- ❑ Health, Wellness, and Disease, p. 511
- ❑ Ethics and Issues, p. 512
- ❑ Stop: Answer the Concept Checks before you go on:
  p. 488 ❑ p. 497 ❑ p. 507 ❑ p. 515 ❑ p. 517 ❑

End of Chapter

- ❑ Review the Summary and Key Terms.
- ❑ Answer the Critical and Creative Thinking Questions.
- ❑ Answer What is happening in this picture?
- ❑ Answer the Self-Test Questions.

CHAPTER OUTLINE

Survival of the Species Depends on Gamete Formation 486

- The Reproductive System Forms and Unites Gametes

The Male Reproductive System Produces, Stores, and Delivers Sperm 488

- The Male Reproductive System Is a Single Tube
- Spermatogenesis Is the Process of Sperm Formation
- Sperm and Semen Are Transported and Stored in Ducts
- The Urethra Runs the Length of the Penis
- The Male Orgasm Propels Sperm
- Male Hormones Control the Rate of Sperm Production

The Female Reproductive System Produces and Nourishes Eggs 498

- Ovaries Are Responsible for Oogenesis—Egg Formation
- The Uterine (Fallopian) Tubes Conduct the Ova
- The Uterus Is the Site of Development
- The Vagina, Vulva, and Many Glands Complete the Female Reproductive System
- The Female Orgasm Is an Emotional and Physiological Epiphany
- Two Hormonal Cycles Occur at Once in Females
- Physiological and Hormonal Changes Are Part of an Integrated System
- Lifestyle Has an Effect on the Female Reproductive Cycle

There Are Many Birth Control Choices 508

- Birth Control Can Be Handled Surgically
- Hormonal Methods of Birth Control Are Another Option
- Elective Abortion Can Take Several Forms
- The Intrauterine Device Provides an Obstruction to Conception
- Spermicides Kill Sperm
- Barrier Methods Block the Entry of Sperm; Some Protect Against STDs
- The Rhythm Method Is Another Viable Technique

Sexual Contact Carries a Danger: Sexually Transmitted Diseases 515

- Knowledge and Prevention Are Your Best Defenses
- STDs Have Many Causes

18.1 Survival of the Species Depends on Gamete Formation

LEARNING OBJECTIVES

1. **Explain** the functions of the reproductive system.
2. **Place** sexual reproduction in the context of the theory of evolution.

Gender is an obvious structural and functional difference between people. We are either male or female. Because we rely on sexual reproduction, having two genders is necessary to perpetuate the species.

Aside from the obvious anatomical differences, are there any homeostatic differences between men and women? Are we so different as to verify the flippant pronouncement "men are from Mars, women are from Venus"? Are we worlds apart just because of a difference in one chromosome? To answer these questions, we will start by looking at reproduction in general and then at male and female anatomy. We will explore hormonal differences and, finally, armed with this knowledge, we will explore methods that help us to control when we reproduce. See *What a Scientist Sees: Man and Woman* for another view of our reproductive system.

gametes Sex cells (eggs and sperm) that join in fertilization.

phenotype An organism's observable characteristics.

alleles Genes found on the same spot on the same chromosome in different individuals, coding for subtle variations of the same protein.

The Reproductive System Forms and Unites Gametes

The main purpose of the reproductive system is to produce **gametes**—egg and sperm—and unite them to form a new individual. Sexual reproduction involves choosing a mate based on **phenotype** and mixing and shuffling genes from the two to form a new individual. This process mixes and blends the **alleles** in the gene pool, creating new genetic combinations.

These new combinations are essential to the survival of the species. The genetic variation in populations of sexually reproducing organisms is the basis for adaptation of organisms to their environment. Given enough variation some individuals will always be better suited to the environment than others. These "more fit" individuals will produce more offspring,

WHAT A SCIENTIST SEES

THE PLANNER

Man and Woman

Sexual reproduction requires two sexes. Humans are dioecious, meaning the male and female reproductive organs are carried on different individuals. In contrast, earthworms and many plants are monoecious; one organism carries both male and female reproductive organs. Also, unlike ants, each of us has reproductive organs; we don't have to rely on a reproductive elite to carry our genes into the future. This reproductive independence ensures that all genes in the population have the opportunity to be passed on to future generations.

Think Critically

1. What might be the benefit to earthworms of being monoecious?
2. Do you think that perceived gender differences are genetically based, or might they be due to our cultural expectations? Can you create an argument supporting the idea that gender differences are founded in cultural practices rather than in genetics?

thereby increasing the percentage of their alleles in the gene pool. This line of reasoning is the underpinning for Charles Darwin's theory of evolution through natural selection. The fittest organisms survive and pass their genes to the next generation.

Passing on your genes requires you to form **haploid** gametes. As we know, *gamete* is a general term for the reproductive cells that will form a new individual, the egg and sperm. These are produced via **meiosis**, a specialized type of cell division that ensures the equal and orderly division of chromosomes. (We will discuss meiosis in detail in Chapter 20.) In order to form gametes properly, the normally **diploid** chromosome number must be cut in half, with the resulting gametes having exactly half the usual complement of alleles. This way, when two haploid gametes unite to form a **zygote**, the original diploid number is restored. The division must be accomplished so that each gamete has a predictable and reliable half of the chromosomes. See Figure 18.1 for an overview of this process.

haploid Having half the number of chromosomes of normal body cells, found in eggs and sperm.

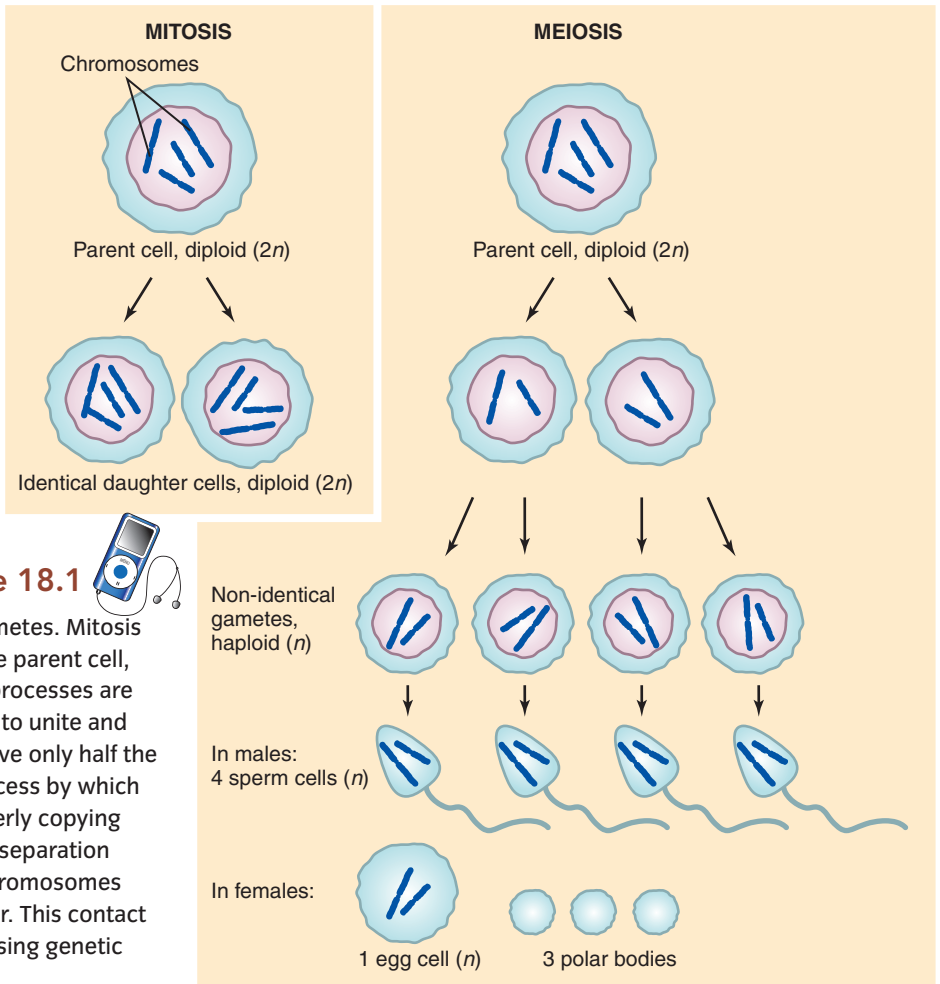
diploid Having the total number of chromosomes of the body cells, twice that of the gametes.

Rather than randomly splitting the chromosomal content of each parent cell, **homologous** chromosomes come together and are then separated, one to each new gamete. The two gametes, the egg and sperm, then come together in a process called **fertilization**, and the resulting cell has one set of chromosomes from each parent.

homologous Similar in structure, function, or sequence of genetic information.

In the male, when meiosis occurs, four sperm are produced from two divisions of a primary **spermatocyte**. Females produce only one egg from each round of meiosis, investing almost all of the cytoplasm and organelles in one gamete. The extra genetic material that is split out is ejected from the developing egg with very little associated cytoplasm. These tiny capsules of DNA are called **polar bodies**. They are not viable, and they are quickly degraded in the female system.

The reproductive system is not finished with the mere formation of gametes: Male and female gametes require



Body cells and gametes • Figure 18.1

Cells divide to produce new cells as well as gametes. Mitosis is the production of two identical cells from one parent cell, and meiosis is the forming of gametes. These processes are covered fully in Chapter 20. If two gametes are to unite and form one new individual, each gamete must have only half the genetic material of the final individual. The process by which gametes are formed (meiosis) involves the orderly copying of DNA from the original body cell and then its separation into four non-identical cells. During meiosis, chromosomes are brought into close contact with one another. This contact allows them to exchange alleles, further increasing genetic variation.

care after they are formed. They need to be united in a protected environment, and the resulting embryo needs to be nourished and protected as it develops. In addition, the reproductive system must:

- trigger puberty
- maintain reproductive ability
- stimulate secondary sex characteristics
- produce hormones involved in sexual maturation and general homeostasis

To accomplish all this, both the male and female reproductive systems are composed of gonads, ducts, accessory glands, and supporting structures. **Gonads** are the organs that produce gametes. **Ducts** transport the gametes and any fertilized egg that is present. **Accessory glands** facilitate gamete production and survival. **Supporting structures** help deliver and support the gametes. Although all four components are found in both men and women, their structures and functions differ with gender, so we'll study each gender separately.

CONCEPT CHECK STOP

1. **What** are the functions of the human reproductive system?
2. **How** does the production of gametes help ensure survival of the species?

18.2 The Male Reproductive System Produces, Stores, and Delivers Sperm

LEARNING OBJECTIVES

1. **Trace** the pathway of sperm through the male.
2. **Describe** sperm production.
3. **Define** the physiological role of orgasm in males.
4. **Outline** hormonal controls in the male.

The function of the male reproductive system is to produce sperm, store it, and deliver it to the female reproductive system. This requires a gonad to produce sperm, some tubes to carry the sperm, three types of accessory glands to produce fluid to sustain the sperm, and several supporting structures to help deliver the sperm. These structures are outlined in Figure 18.2.

The Male Reproductive System Is a Single Tube

The male reproductive system is essentially one long tube, with sperm generated in the gonads at one end, matured along the route, and released from the body at the other. Accessory glands add secretions to nourish and carry the sperm before it is released.

Sperm is produced in the testes. The testes are paired organs suspended in the **scrotal sac**, where their internal temperature can be regulated with ease. Viable sperm can only be produced at temperatures 2° to 3°C below normal body temperature. The muscles of the scrotal sac move the testes to regulate their temperature—the muscles contract when the temperature drops. This contraction elevates the testes, bringing them closer to the body and thus maintaining the required temperature by allowing the testes to absorb heat from the body. When the temperature within the testes rises, the muscles relax and the testes move away from the body, reducing their internal temperature. Figure 18.3 on page 490 shows the testes and their supporting structure.

The male reproductive organs usually begin development seven weeks after conception, forming from the embryonic mesonephros duct. By seven months after conception, the testes migrate from their developmental position in the abdominal cavity to the scrotal sac, dragging their associated vessels, nerves, lymph, and reproductive cords with them. Their path leaves a weak spot in the abdominal wall, which can lead to a hernia later in life. A hernia

is a rupture of the abdominal wall accompanied by the protrusion of internal organs, usually the small intestine. Hernias often require surgery to reposition the protruding organs and close the hole.

This "descending" of the testes is vital to reproductive health. Recall that production of viable sperm requires a temperature 3°C below body temperature. If the testes do not descend, the seminiferous tubules inside the testes will be too warm for sperm creation. Additionally, when the testes remain in the body cavity, they are far more prone to testicular cancer.

In 3% of full-term male births and a full 30% of premature male births, the testes have yet to descend. The medical term for this condition is **cryptorchidism**, literally "hidden orchid." The male will be sterile if both testes remain in the body cavity. Luckily, among approximately 80% of cryptorchid males, the testes naturally descend within the first year. If they do not descend by 18 months, surgery is needed.

In normal development, each testis carries out **spermatogenesis** independently within the individual pouches of the scrotal sac. The testes are actually a densely packed mass of **seminiferous tubules** contained in 200 to 300 lobules within each testis. An individual lobule holds up to three tubules, providing a large number of seminiferous tubules per testis. See Figure 18.3.

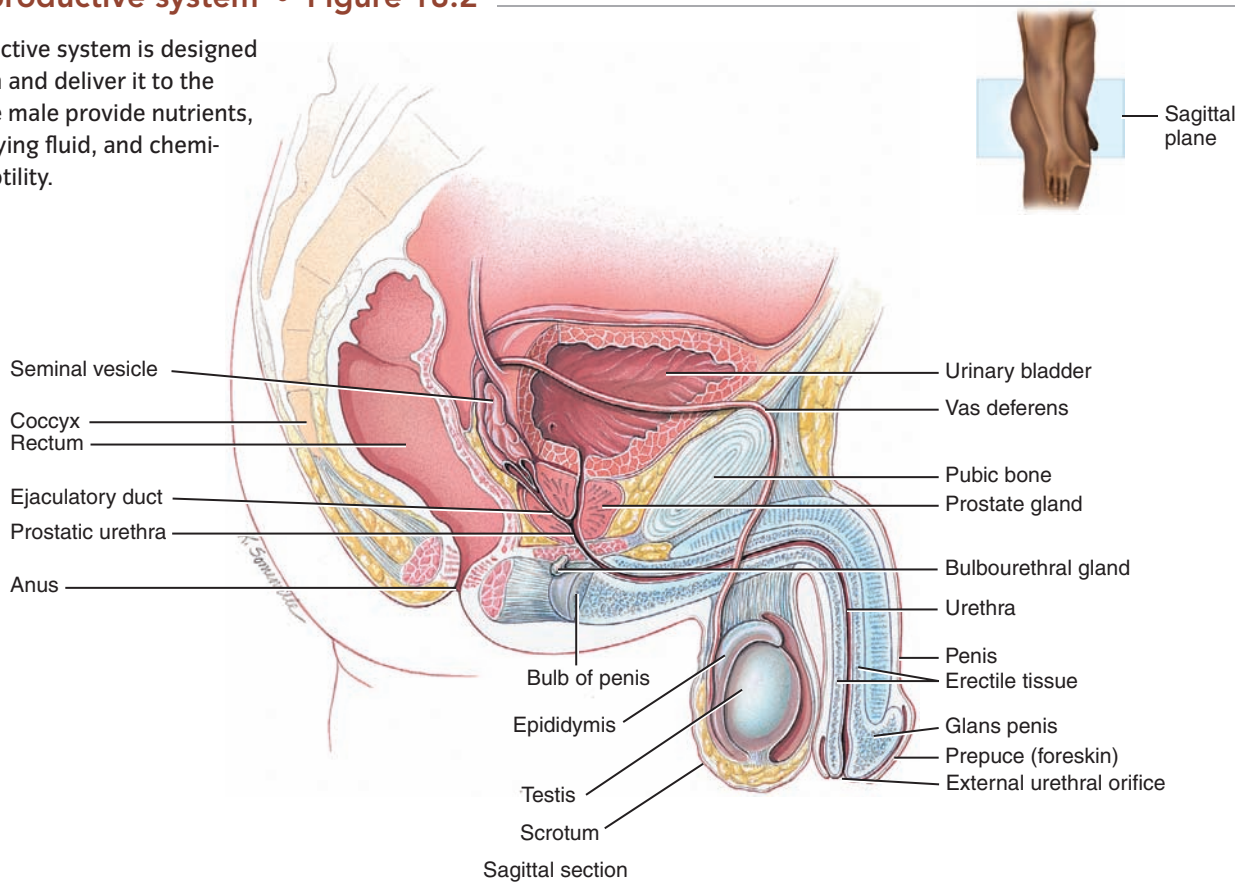
spermatogenesis
The formation of sperm cells.

The cells that produce sperm are found lining the seminiferous tubules. Within the seminiferous tubules are two types of cell: **spermatogenic** cells and **Sertoli** cells. At puberty, the spermatogenic cells are stimulated to begin producing sperm. They first divide into spermatogonia. Spermatogonia in the walls of the seminiferous tubules divide, forming **primary spermatocytes**. As these cells continue to divide, they are pushed farther from the wall of the tubule into the lumen, where they become secondary spermatocytes and then **spermatids**.

During this stage of development, the cells become progressively less like the cells of the male body and more like separate entities. Eventually they become so different that these spermatids need protection from the host male's immune system, which would otherwise destroy them as foreign cells. The Sertoli cells extend from the basement membrane of the seminiferous

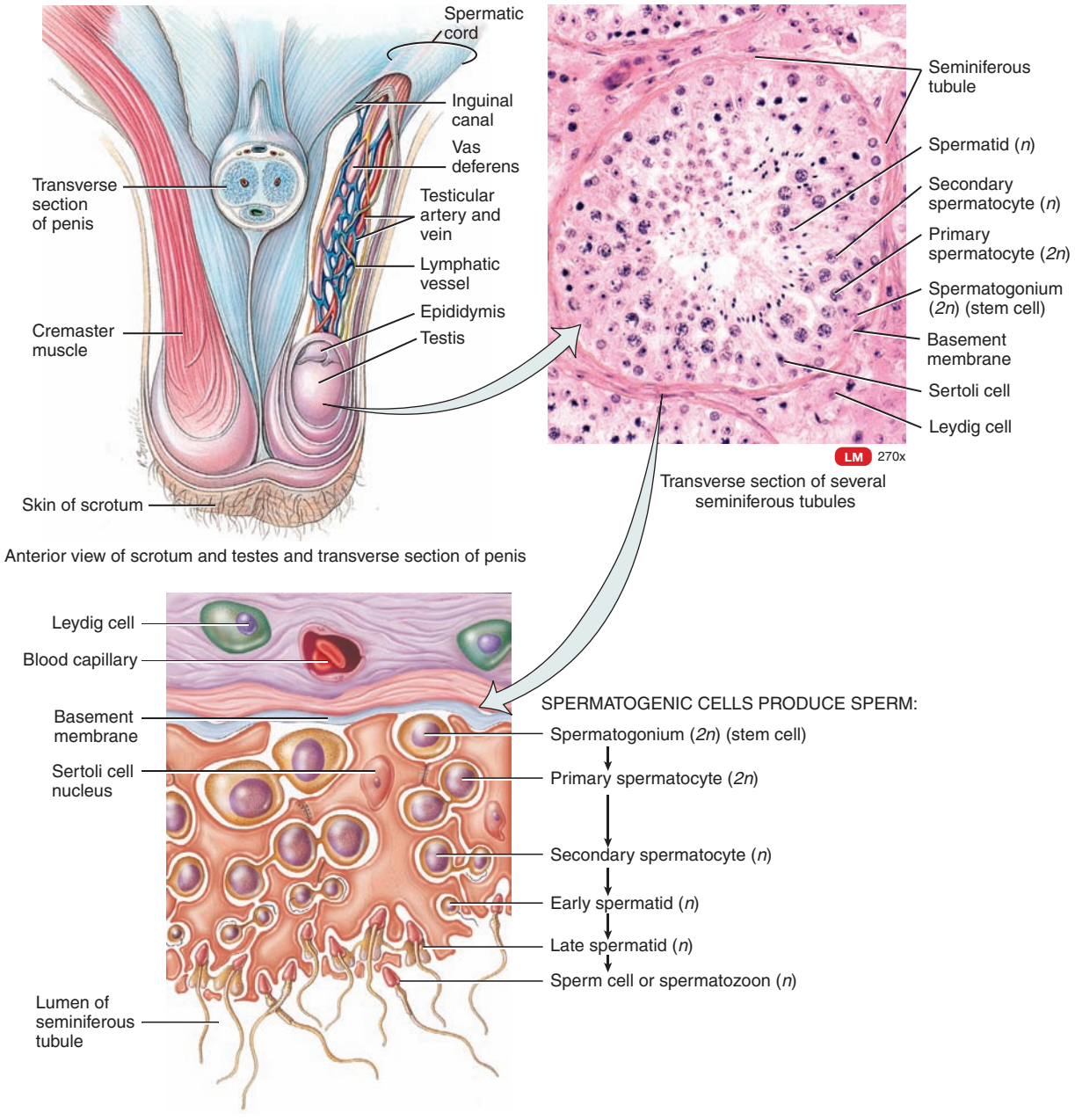
The male reproductive system • Figure 18.2

The male reproductive system is designed to produce sperm and deliver it to the egg. Glands in the male provide nutrients, a supportive carrying fluid, and chemicals for sperm motility.



The testes and their supporting structure, the scrotum • Figure 18.3

Sperm cannot be produced at temperatures above 35°C. Tight clothing restricts the movement of the testes, holding them closer to the body and reducing fertility.



tubule all the way to the lumen. Their job is to surround the developing sperm, isolating it from the male's blood supply as protection against immune attack. The only cells of the seminiferous tubule that do not require protection are the spermatogonia. These cells are identical to those of the male body, so they are in no danger of attack (see Figure 18.3).

Beyond protecting the developing sperm, the Sertoli cells also assist in their survival. They provide nourishment for the developing sperm, assist in the final maturation of sperm by removing excess cytoplasm, control the release of sperm into the seminiferous tubule lumen, and mediate the effects of the hormones testosterone and inhibin.

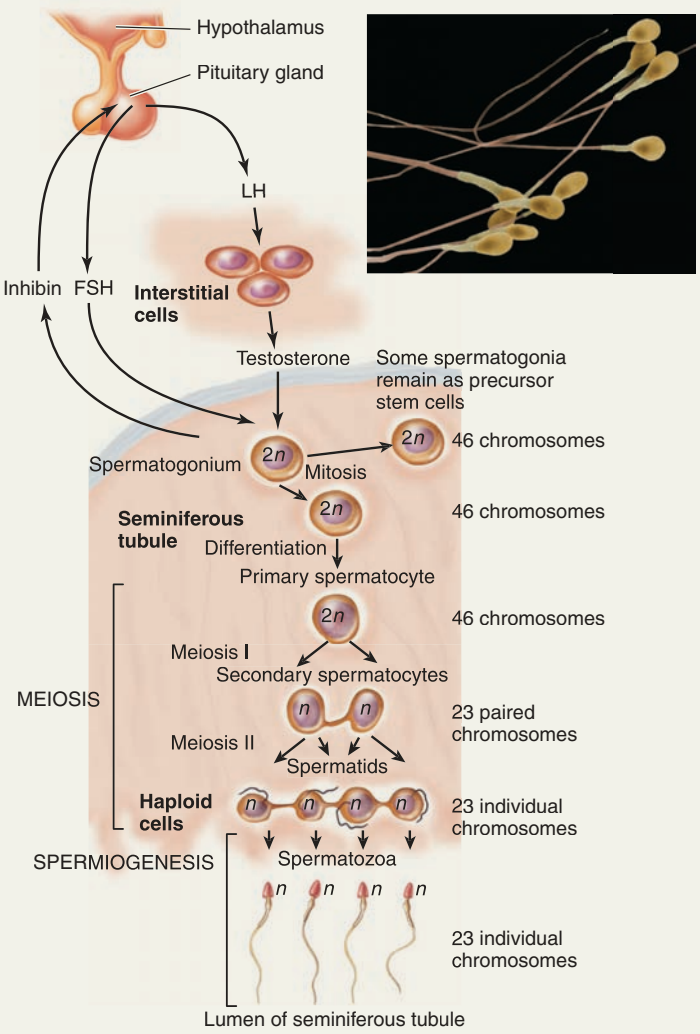
One final type of cell in the testes occurs outside the seminiferous tubules, between them in the lobules. The **Leydig** cells, or interstitial endocrinocytes, produce the hormone **testosterone**. Testosterone stimulates sper-

Biological InSight

Sperm formation (spermatogenesis) • Figure 18.4

THE PLANNER

Spermatogonia undergo mitosis and produce two cells: one cell that migrates into the center of the seminiferous tubule becoming a primary spermatocyte, and a second one that remains on the periphery. The primary spermatocyte then undergoes meiosis I, producing two secondary spermatocytes. These spermatocytes go on to complete meiosis, producing a total of four spermatids. Once these spermatids undergo spermiogenesis, four functional sperm are produced.



matogonia to produce sperm; stimulates bone growth; increases hair production on the arms, legs, underarms, chest, groin, and face; stimulates cartilage growth of the larynx (thereby lowering the voice) and increases libido. In short, testosterone from the Leydig cells turns the adolescent male into a fully reproductive man.

Spermatogenesis Is the Process of Sperm Formation

The process of making and maturing a sperm cell (called a spermatozoon) takes 65 to 75 days. It begins with the spermatogonia, which are **stem cells**. When the spermatogonia divide, one cell remains in contact with the basement membrane as a spermatogonium and the other moves toward the lumen to begin the process of spermatogenesis. This second cell moves into a Sertoli cell and transforms into a primary spermatocyte. Both primary spermatocytes and spermatogonia are diploid cells. Once safely protected by the Sertoli cells, meiosis can occur. At the end of the first round of meiosis, two secondary spermatocytes are formed. Each secondary spermatocyte contains 23 paired chromosomes, too many for one gamete.

stem cells
Undifferentiated cells that remain able to divide and specialize into functional cells.

As meiosis proceeds, each secondary spermatocyte divides further to produce two haploid spermatids. This division yields a total of four haploid cells carrying the DNA of a sperm but without the characteristic shape of the sperm cell. During the process of **spermiogenesis**, the correct shape is acquired, as seen in Figure 18.4. The newly

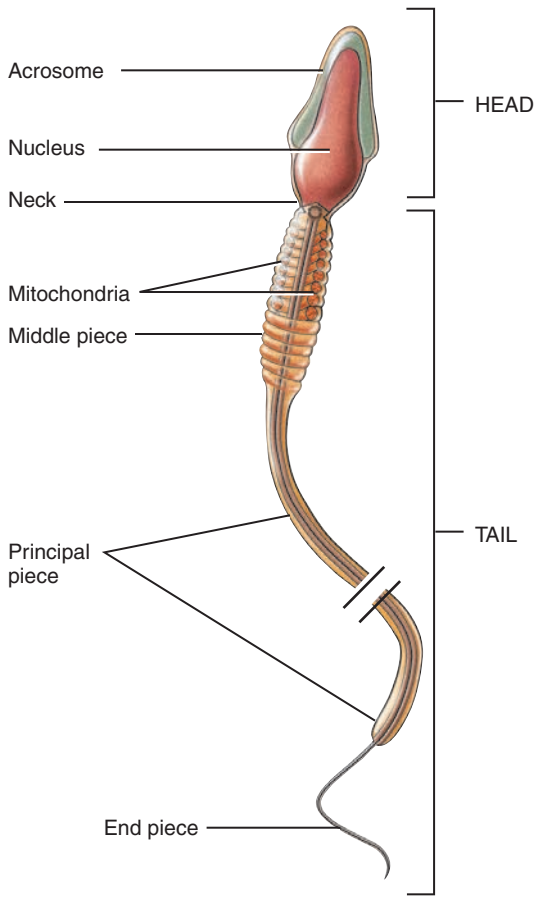
formed spermatids are slowly ejected from the Sertoli cell as they mature. When the sperm are free of the seminiferous tubule, they are called spermatozoa (singular: *spermatozoon*) and are fully formed, if not yet activated (capable of fertilizing an ovum).

A normal male produces about 300 million sperm per day from puberty until death. Sperm exist to reach and penetrate an egg, and each part of the sperm has a role in meeting this goal. The head of the sperm includes the **acrosome** and the nucleus, as shown in Figure 18.5. The acrosome is a vesicle on the point of the sperm head that contains digestive enzymes. These will be useful when the sperm encounters the egg, as it will digest the **oocyte** membrane, allowing the nucleus of the sperm to penetrate. The midpiece of the sperm contains many mitochondria that produce the ATP needed to reach the egg. The tail of the sperm consists of one long flagellum. The sperm is the only human body cell with a flagellum and is one of few human cells that must propel itself from its place of origin in order to perform its function.

oocyte Egg; the female gamete.

Sperm • Figure 18.5

The sperm carries its genetic material in its oval head. As you can see, the sperm is more tail than head, to assist in "swimming" toward the egg. Sperm vary in their "motility," their ability to swim in a relatively straight line to the egg. If a large percentage of sperm don't swim at all, or swim in circles, the result is usually infertility.



Sperm and Semen Are Transported and Stored in Ducts

Once sperm is produced in the seminiferous tubules, it must be transported from the male to the female. This move requires a series of ducts through which the sperm will pass. **Semen**, the fluid containing sperm and other ions, is formed as the sperm traverses these ducts.

The Sertoli cells create a fluid that fills the seminiferous tubule lumen and pushes the developing spermatozoa along. The spermatozoa leave the seminiferous tubules in the lobules of the testes and travel to the rete testes, the network of tubules found at the junction of the testis and the epididymus, before leaving the testis. The rete testis ends at the **epididymis**.

The function of the epididymis is similar to that of the aging cellar at a winery. It serves as a storage area and final maturation center for the spermatozoa, just as the casks at a winery serve as a suitable environment for the young wine to age and mature before being sold. Spermatozoa reach final form in the epididymis, losing that last bit of excess cytoplasm while gaining mobility and the ability to fertilize an ovum. This process takes about 10 to 14 days. Spermatozoa can remain **quiescent** in the epididymis for approximately one month. If an ejaculation event occurs, the walls of the epididymis aid in propelling the sperm forward. A small peristaltic wave is generated in the smooth muscle of the wall, helping to push the spermatozoa into the next tube in the system, the **vas deferens** (also called the ductus deferens in clinical and medical terminology).

quiescent Resting, quiet, inactive.

The vas deferens transports and stores sperm. The vas deferens runs approximately 50 centimeters from the epididymus in the scrotal sac through the abdominal wall, looping over the **ureter** and running behind the urinary bladder. It begins at the tail of the epididymis, where the epididymal tube expands in diameter. As the vas deferens enters the abdominal wall, it

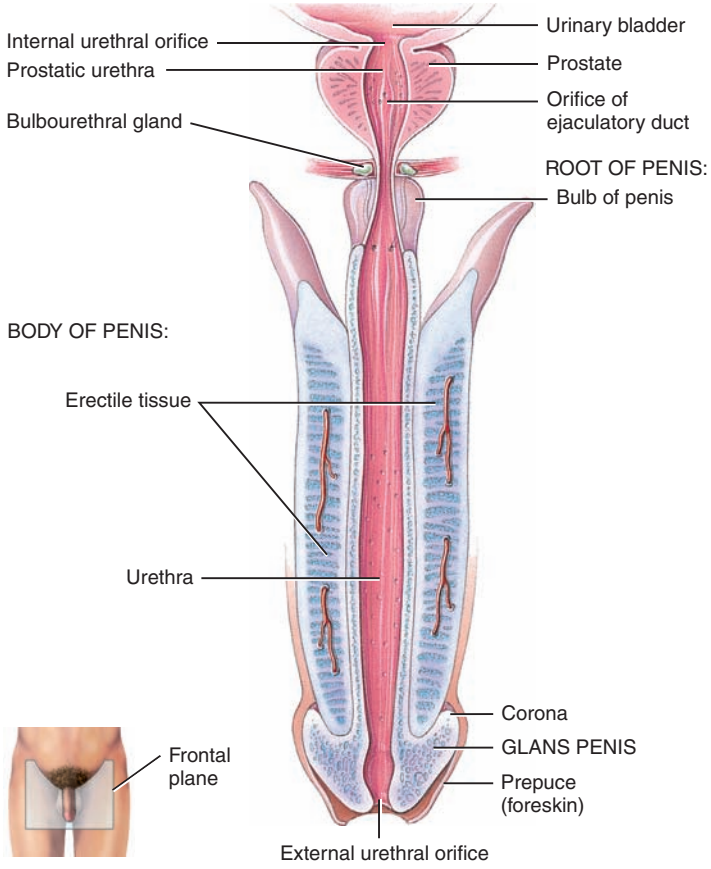
spermatic cord The artery, vein, nerve, lymphatics, and vas deferens that lead from the abdominal cavity to the testes.

sits at the anterior of the **spermatic cord**, readily accessible immediately beneath the skin of the scrotum. The length of the vas deferens is used to store sperm for as long as several months. If there is no ejaculation during that time, the sperm are broken down and reabsorbed. The placement of the vas deferens and its function as a sperm transport vessel make it a prime candidate for sterilization surgery. You may have heard of a vasectomy; the term literally means "cutting the vas deferens." (This procedure is explained in the section on birth control near the end of this chapter.)

Seminal vesicles help nourish the sperm. Glands add fluid to the developing semen as it moves through the male system during ejaculation. The paired **seminal vesicles**, located on the posterior base of the urinary bladder, are the first of these glands. They secrete an alkaline, fructose-rich fluid that serves two purposes. The high pH helps to neutralize the potentially lethal, acidic environment of the male urethra and the female reproductive tract. The fructose serves as an energy source for the sperm as they become motile. **Prostaglandins** are also released by the seminal vesicles. Prostaglandins have many physiological effects. They open airways, stimulate the sensation of pain, reduce stomach acid production, and cause local irritation. Prostaglandins also seem to stimulate sperm motility. A final important component of seminal vesicle fluid is a clotting factor, which may be responsible for the coagulation of semen after ejaculation. In all, the seminal vesicles secrete approximately 60% of the total ejaculate volume.

The ejaculatory duct runs through the prostate gland. After leaving the seminal vesicles, sperm travels along the short ejaculatory duct to the prostatic urethra. The union of the terminal end of the vas deferens and the duct from the seminal vesicle marks the beginning of the ejaculatory duct. Semen does not reach this duct except during ejaculation. During an ejaculation, sperm and semen are forcefully pushed into the prostatic urethra, causing the prostate gland to add secretions.

The prostate gland is a golf ball-sized gland lying immediately at the base of the bladder, as seen in Figure 18.6. It completely surrounds the uppermost portion of the urethra, secreting a milky fluid into the passing semen. This fluid includes citric acid for ATP production, proteolytic enzymes to break up the clot formed by the seminal vesicle secretions, and acid phosphatase, whose function is unclear. Another 25% of the semen volume comes from this gland.



The prostatic urethra and penis • Figure 18.6

The prostate gland surrounds the prostatic urethra. The penis is usually divided into the root, body (or shaft), and glans. The body of the penis contains several cylinders of erectile tissue, the ends of which form the glans.

The Urethra Runs the Length of the Penis

Once through the prostatic urethra, the semen travels through the remaining portion of the urethra. Immediately upon leaving the prostate, the urethra dives through the **urogenital** diaphragm. It then continues the length of the penis, through the spongy (or penile) urethra and to the external urethral orifice.

urogenital Concerning both the urinary and reproductive systems.

Where the urethra enters the spongy tissue of the penis, a final set of glands adds fluid to the ejaculate. The **bulbourethral** glands lie on either side of the urethra, at the bulb, or base, of the penis. The glands are obviously named for their location. They secrete an alkaline, mucous fluid into the urethra prior to sperm arrival that protects the sperm from the normally acidic urethra. The mucus of these glands lubricates the tip of the penis and the urethral lining, preventing damage to the sperm as they travel the final portion of the male reproductive system. Refer to Figure 18.6 for the locations of these structures.

The penis is a passageway for both urine and semen. As you know, the male urethra functions from birth to death as a conduit for urine leaving the bladder. After puberty, the urethra is also used by the reproductive system to transport sperm from the body. This dual use requires a check valve at the junction of the bladder and the urethra so that only one fluid is present in the urethra at a given time. During an ejaculation, urine is prevented from leaving the bladder and semen cannot travel up into the bladder. The **root** of the penis lies at the base of the prostate gland. The body of the penis contains several cylinders of erectile tissue, one of which encircles the urethra and expands at the tip of the penis to form the **glans**. These tissues contain numerous blood sinuses. See *I Wonder… Why Are Circumcisions Performed?* for more information on this practice.

cGMP allows more blood to enter erectile tissue. During sexual arousal, the arteries that feed the erectile tissue dilate under the influence of cyclic guanine monophosphate (**cGMP**). cGMP allows more blood to enter the erectile tissue, filling the sinuses and compressing the veins. This combination results in an **erection**, an enlarged and stiffened penis. This process is reversed by constriction of the arteries, in turn lessening the pressure on the veins and allowing blood to drain from the tissues. Viagra inhibits enzymes that naturally break down cGMP, thereby prolonging erections. cGMP is active in other processes in the body as well—for example, in processing visual and olfactory information, in memory, and in learning. The cGMP inhibitors in Viagra are extremely specific; otherwise, the drug would have negative side effects on memory and vision.

cGMP Cyclic guanine monophosphate, an energy molecule.

I WONDER…

THE PLANNER

Why Are Circumcisions Performed?

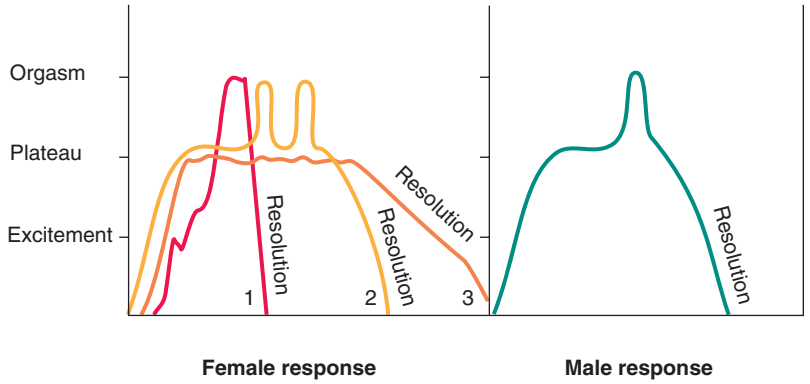
Circumcision began long ago. When boys are born, the tip of the penis is covered with a protective layer of skin, called the foreskin. Circumcision involves the rapid removal of the entire foreskin of the penis, usually within the first few days of life. Removal of this tissue does not seem to alter male functioning, nor does it have any clearly demonstrated positive physiological effects, except that removal has been shown to reduce the rate of infection by the AIDS virus. Neonatal circumcision produces fewer side effects and less bleeding than adolescent and adult circumcision.

Male circumcision continues to be practiced in the United States and other countries around the world. The World Health Organization estimates that approximately 30% of the world's male population is circumcised.

A number of studies have shown that the foreskin may transmit AIDS during sex because HIV seems to bind strongly to the foreskin. One study from India found that circumcised men were six times less likely to acquire HIV during sex. Some think these findings may lead to a rise in the circumcision rate worldwide.

Four phases of human sexual response • Figure 18.7

The four phases of human sexual response are not without some controversy. Research conflicts on whether women need more time to become aroused than men and whether the female orgasm plays any role in fertilization (muscular contractions might help move the sperm toward the egg).



The Male Orgasm Propels Sperm

Male and female sexual responses share some similarities. In both sexes, blood flow to the genitals is altered, gland secretion increases, and orgasm results in rhythmic contractions of pelvic muscles. In the mid-1950s, sex researchers Masters and Johnson began research on the human sexual response that spawned the study of human sexuality. They identified four phases of the human sexual response, which appear in both males and females: arousal, plateau, orgasm, and resolution, as shown in Figure 18.7.

For males, during **arousal** (or excitement), blood flow to the penis is altered, glands begin to secrete lubricating fluids, and heart rate and blood pressure increase. Arousal is governed by the parasympathetic nervous system. This phase is highly responsive to sensory stimulation, such as touching of the genitals. Other sensory stimulation, including visual, auditory, or even olfactory stimuli, can increase or dampen the arousal.

As excitement builds, **plateau** is reached. This can last from a few seconds to many minutes.

Orgasm, a series of wave-like muscular contractions along with an intense pleasurable sensation, marks the end of the plateau. Orgasm and resolution are controlled by the sympathetic nervous system. In the male, orgasm accompanies ejaculation. Once males reach orgasm, they experience a refractory period of a few minutes to a few hours. During this time, a second ejaculation is physiologically impossible.

The last phase, **resolution**, begins with a sense of intense relaxation. Heart rate, blood pressure, and blood flow all return to prearousal levels. Resolution time is variable, taking longer to arrive when no orgasm occurred.

Directed by the sympathetic nervous system, the male orgasm propels sperm from the epididymis through the vas deferens, the ejaculatory duct, and the urethra, releasing it from the male body. As sperm enter the ejaculatory duct from the vas deferens, the prostate and bulbourethral glands add their secretions, creating semen. Rhythmic, reflexive contractions of pelvic muscles cause the semen to be released from the penis in short bursts. During this reflex, the sphincter at the base of the urinary bladder closes, preventing urine from entering the urethra and sperm from entering the urinary bladder.

The total ejaculate released during orgasm is usually 2.5 to 5 ml. On average, there are between 50 and 150 million sperm per ml, for a total of over 350 million sperm per ejaculate. Obviously, the male reproductive strategy is to release a flood of sperm to increase the odds of fertilization. If the sperm count drops below 20 million per ml, the male is said to be infertile. This number is usually too low to fertilize an egg, because so few of the ejaculated sperm reach the ovum.

Often, a slight emission precedes ejaculation, as a peristaltic wave passes through the ejaculatory duct, vas deferens, seminal vesicles, and prostate. The emission cleanses the urethra, removing potentially harmful crystals that might impair sperm function. Although most ejaculations occur during the stimulation of sex, men can also experience "nocturnal emissions," or ejaculations during sleep. These are normal, and may or may not be associated with sexually arousing dreams.

Male Hormones Control the Rate of Sperm Production

Although it is true that males produce sperm endlessly from puberty until death, male hormones exert control over the rate of sperm production and the secretion of testosterone, which controls male secondary sex characteristics. The pituitary gland lies deep in the brain, protected by the sphenoid and attached to the brain by the hypothalamus. The anterior pituitary gland secretes **luteinizing hormone** and **follicle-stimulating hormone**, which are instrumental in governing the male

reproductive system. The secretion of these hormones is governed by gonadotropin-releasing factors produced by the hypothalamus.

The names of these two hormones reflect their roles in the female, not male, system. When reproduction was originally studied, it was assumed that only females exhibited hormonal controls. Therefore, these anterior pituitary hormones were first isolated and their functions were identified in females. Follicle-stimulating hormone (FSH) stimulates immature oocyte (egg) follicles in the female ovary. Luteinizing hormone (LH) stimulates the production of a yellow body; lutein roughly translates to yellow. After an oocyte is ovulated, a yellow body remains on the ovary, hence the name of the hormone responsible for ovulation. It came as a bit of a shock when scientists later discovered that the male pituitary secretes the same hormones, with subtly different effects.

Luteinizing hormone (LH) stimulates the release of testosterone. In the male, luteinizing hormone (LH) stimulates the Leydig cells residing between the seminiferous tubules, causing the release of testosterone. For this reason, it is also called interstitial cell stimulating hormone (ICSH). The production of testosterone is governed by a typical negative feedback loop. As more testosterone is produced, its levels increase, inhibiting production of LH at the pituitary gland. In this way, the hormones testosterone and LH balance one another.

The functions of testosterone include stimulation of male patterns of development in utero, enlargement of male sex organs during puberty, development of male secondary sex characteristics, development of sexual function, and stimulation of anabolism (the building of larger molecules from smaller ones).

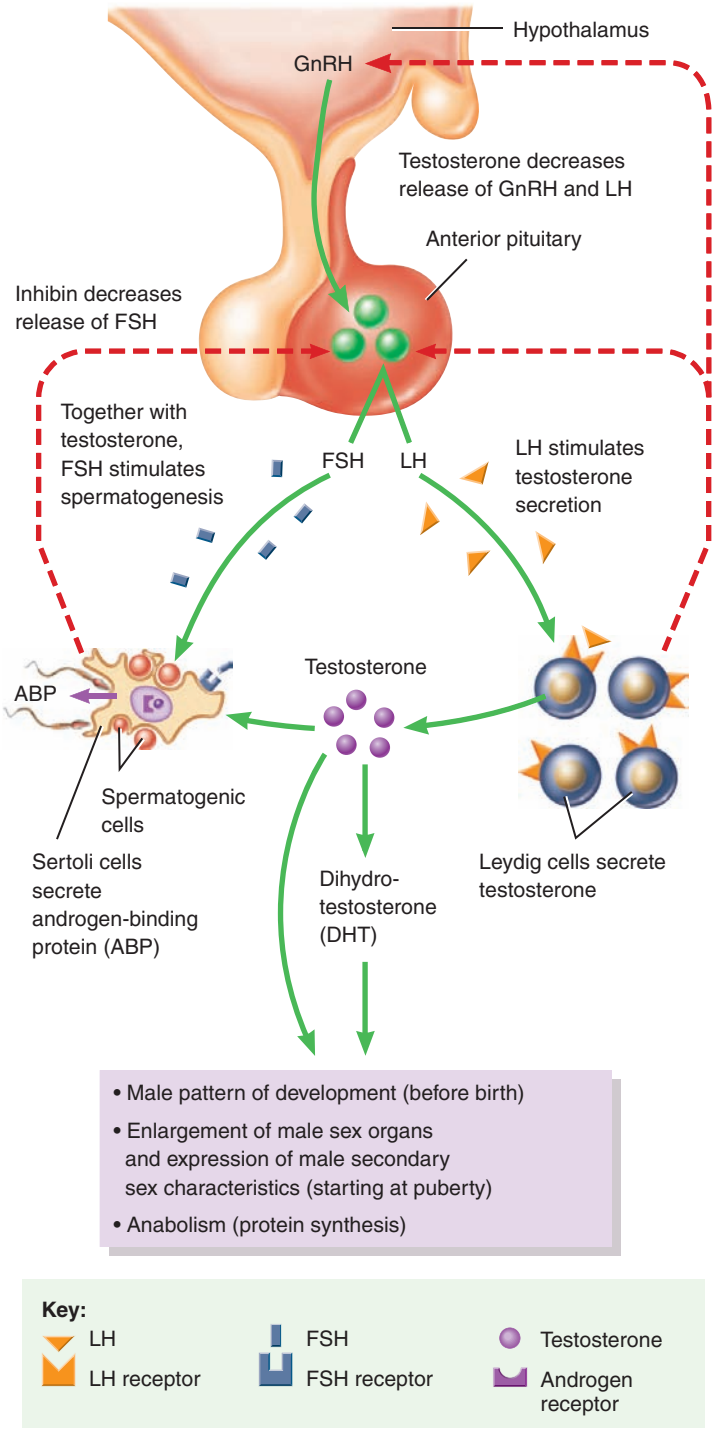
Secondary male sex characteristics are those associated with puberty: growth of skeleton and musculature; appearance of body and facial hair; cartilaginous growth of the ears, nose, and larynx; thickening of the skin; and increased oil secretion in the skin. Some tissues of the male convert testosterone to **dihydrotestosterone**, or DHT. You may have heard this compound being blamed for male pattern baldness on Web sites or television infomercials, which make it sound as if everybody's hair will fall out if DHT concentration exceeds a certain level. In truth, male pattern baldness is due to varying sensitivity of hair follicles to circulating DHT. Hair follicles can produce the enzyme 5-alpha reductase, which converts circulating testosterone into dihydrotestosterone (DHT). This conversion raises the concentration of DHT around the follicles. Also, DHT gets held by those hair follicles that have many DHT receptors. A DHT-activated hair follicle has a shorter growing stage and a longer "resting" phase and will produce wispy hair. DHT also constricts blood vessels to the follicle, starving the hair of nutrition. All these factors eventually cause the hair to fall out, and any replacement hair will be thin and slow growing. This extreme reaction to DHT is genetic, as are the patterns and numbers of susceptible hair follicles on the head. Because factors that increase the likelihood of developing male pattern baldness are carried on the X (female) chromosome, it is considered a sex-related trait, as shown in **Figure 18.8**.

Male pattern baldness is hereditary • Figure 18.8

Three generations of men, showing the quirky nature of male pattern baldness. Although both father and grandfather are losing hair, the son appears not to suffer hair loss. This is possible because the gene for DHT sensitivity is passed from mother to son, not father to son. Additionally, the level of the hormone DHT plays a major role. If the man does not produce high levels of DHT, he will not experience hair loss, regardless of his genetic makeup.

Hormonal control of male reproduction • Figure 18.9

The dashed red lines indicate negative feedback inhibition.



Follicle-stimulating hormone (FSH) indirectly stimulates spermatogenesis. FSH is secreted by the anterior pituitary gland in both sexes. In the male, where oocyte follicles are absent, FSH indirectly stimulates spermatogenesis. FSH and testosterone together cause the Sertoli cells to secrete **androgen-binding protein** (ABP). ABP moves to the interstitial spaces of the testes, binding available testosterone and maintaining it in high concentration near the seminiferous tubules. Testosterone stimulates the final production of spermatids. When the Sertoli cells are functioning to capacity to protect developing sperm, they secrete **inhibin**. This hormone inhibits FSH production from the anterior pituitary, slowing sperm production. In essence, the Sertoli cells are claiming that they are "full" and cannot protect any more developing sperm. In typical negative feedback, if sperm production slows too much, the process reverses. The Sertoli cells no longer release inhibin, the anterior pituitary increases production of FSH, and sperm production rises.

What causes testosterone levels to vary? Testosterone itself also operates under negative feedback. If blood testosterone rises too high, it prevents the release of **GnRH** (gonadotropin-releasing hormone) from the hypothalamus. When released, GnRH goes directly to the anterior pituitary and stimulates release of LH. Recall that LH then increases secretion of testosterone by Leydig cells. If GnRH is blocked, LH is not released and the testosterone level will decline, as seen in Figure 18.9.

CONCEPT CHECK

1. **What** is the pathway of sperm through the male?
2. **How** are sperm produced?
3. **What** does FSH stimulate in the male? LH?
4. **What** is the physiological role of the male orgasm?

18.3 The Female Reproductive System Produces and Nourishes Eggs

LEARNING OBJECTIVES

1. **List** the functions of each female reproductive organ.
2. **Explain** oogenesis.
3. **Describe** the female hormonal cycles.

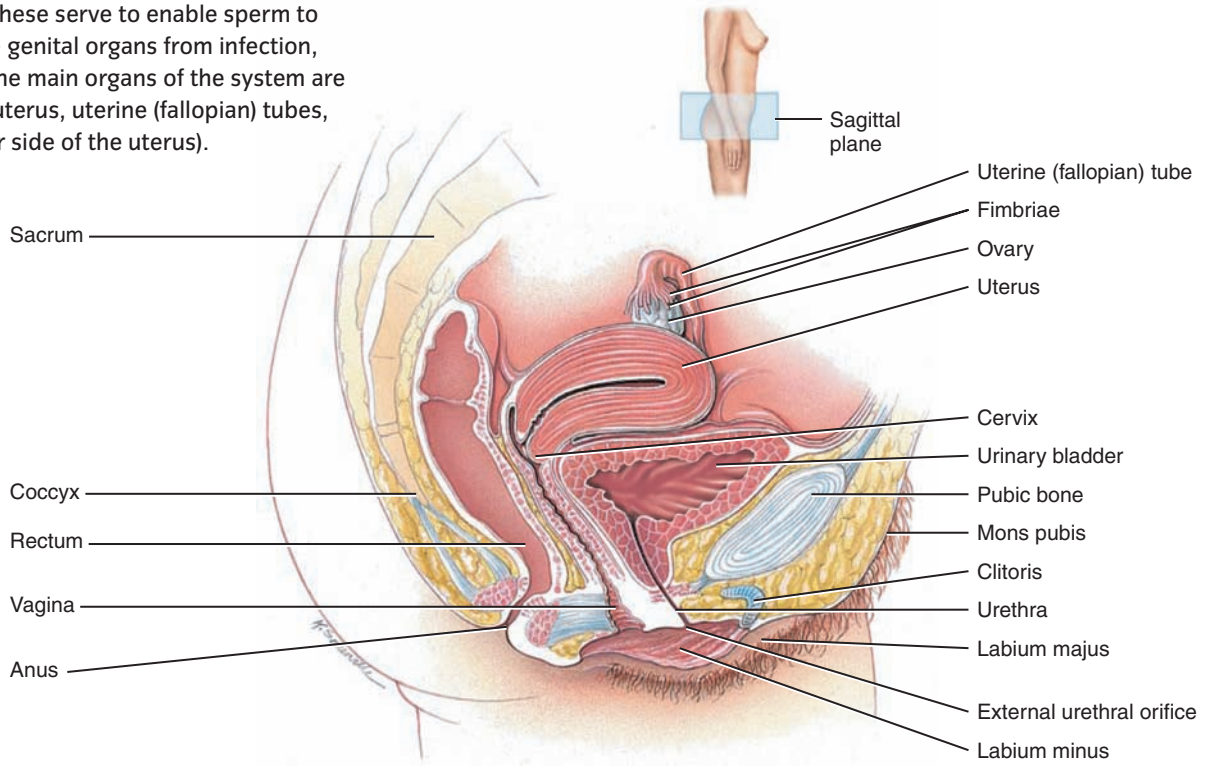
If the purpose of the male reproductive system is to deliver sperm, one purpose of the female reproductive system must be to receive sperm. In addition, though, the female system must also produce eggs (or **ova**) for fertilization, provide an area for the fertilized egg to develop into a fully developed fetus, and give birth. Like the male reproductive system, the female system also produces hormones that cause sexual maturity and stimulate the development of secondary sex characteristics.

The organs of the female reproductive system include the paired **ovaries**, the **fallopian** or **uterine tubes** leading from the ovaries to the uterus, the **uterus** itself, and the **vagina**, as seen in Figure 18.10. Accessory organs of the female system are fewer than in the male system, and are represented mainly by the **mammary** glands and the external female genitalia.

Although the anatomy of the female reproductive system is simpler than that of the male, the hormonal control of the female system is far more complex. This is because two interacting hormonal cycles occur simultaneously in the female. The anterior pituitary gland secretes FSH and LH, affecting the ovary, and the ovary then responds with the hormones **estrogen** and **progesterone** that affect the uterus. Ovarian hormones can inhibit the anterior pituitary gland, providing feedback control.

The female reproductive system • Figure 18.10

The female reproductive system has external and internal components. The labia, clitoris, and external urethral orifice are external. These serve to enable sperm to enter and protect the genital organs from infection, among other roles. The main organs of the system are internal: the vagina, uterus, uterine (fallopian) tubes, and ovaries (on either side of the uterus).



Sagittal section

Ovaries Are Responsible for Oogenesis—Egg Formation

atresia Reabsorption of immature ova prior to birth.

The ovaries are small, almond-shaped organs that lie in the pelvic cavity. They arise from the same embryonic tissue as the testes, making testes and ovaries homologous. Similar to the testes, the ovaries produce both gametes (ova, singular: *ovum*) and hormones (**estrogens** and **progesterone**). **Oogenesis** occurs via meiosis but, unlike spermatogenesis, produces only one viable ovum per meiotic event, as seen in Figure 18.11.

Also unlike the production of sperm, oogenesis begins before the female is born, so that at birth the ovaries already contain all of the ova she will produce in her life. The ova are found in the ovarian germinal epithelium at the center of the ovaries, surrounded by the ovarian cortex. The ova wait there, suspended in early meiosis, until they receive hormonal signals to continue development. At birth, each ovary may contain from 200,000 to 2 million such cells. These **primary oocytes** undergo **atresia**, so that by puberty approximately 150,000 to 200,000 remain in each ovary, or about 300,000 to 400,000 in both ovaries. Only 400 or so of these will actually mature to the point of ovulation during a woman's reproductive lifetime.

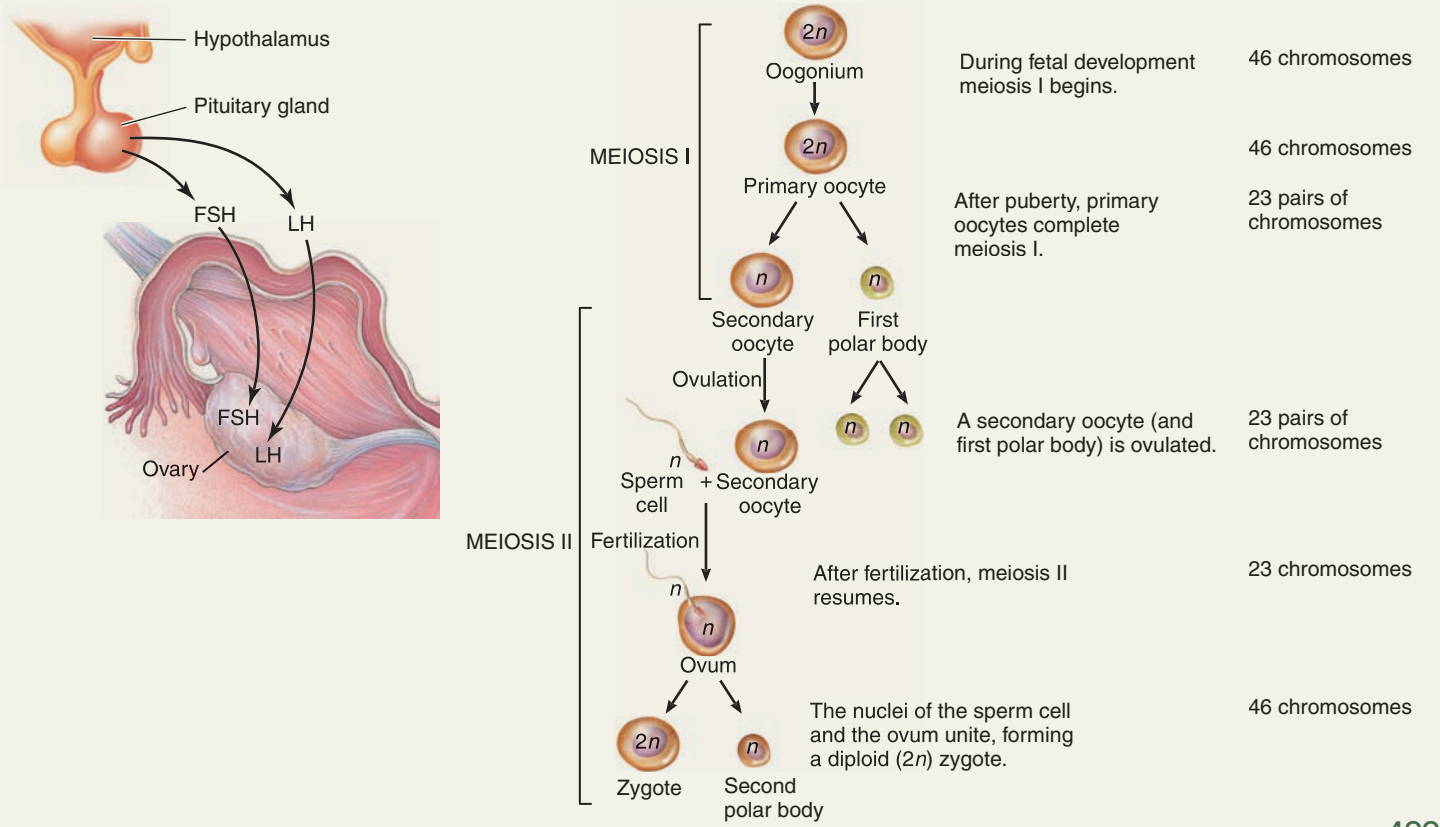
Each primary oocyte sits in the center of a group of **follicular cells**, which are stimulated to develop alongside the oocyte. A **primary follicle** has one to seven layers of follicular cells surrounding the oocyte. These follicular cells produce a clear gel-like layer that surrounds the maturing oocyte.

Hormones released by the anterior pituitary gland affect these follicle cells, stimulating their maturation into a secondary follicle, and finally a mature, blister-like **graafian follicle**. The graafian follicle bursts during ovulation, releasing the secondary oocyte into the pelvic cavity. Only if sperm are present and fertilization occurs will the secondary oocyte complete meiosis to form an ovum. The ovulated egg itself is short-lived, remaining viable for about 24 hours. Therefore, either the immature egg is fertilized by

Biological InSight

Egg formation (oogenesis) • Figure 18.11

THE PLANNER



the sperm within 24 hours, resulting in a **zygote**, or it degenerates and passes from the female body with the next menses. See Figure 18.12 for an overview of follicular development.

The Uterine (Fallopian) Tubes Conduct the Ova

Once the oocyte is ovulated, it must be swept into the uterine tubes. The open ends of the uterine tubes are expanded into a funnel-shaped **infundibulum** that ends in finger-like **fimbriae**. These tubes are extremely close, but not physically connected, to the ovaries. The fimbriae must collect the ovulated oocyte and sweep it into the infundibulum. Successful pregnancy can occur only in the uterus, so the fimbriae must get the newly ovulated egg heading in the right direction. The fimbriae accomplish this by swaying rhythmically in response to the hormonal controls of ovulation. The ends of these tubes fill with blood, distend, and sway, creating small currents in the abdominopelvic fluid, in turn drawing the newly ovulated oocyte into the uterine tubes. Once the oocyte is collected in the uterine tube, ciliated epithelia lining the tube help wash the oocyte (or developing zygote if fertilization occurs) into the uterus. Smoking can inhibit the movement of the cilia of the uterine tube; this is one reason why women who smoke have difficulty conceiving.

Because the oocyte is only viable for a short while, fertilization must occur within 24 hours of ovulation. Usually the egg can travel only the upper one-third of the uterine tubes during this time, meaning that if fertilization does occur, it will happen there. The oocyte takes six to seven days to reach the uterus, during which time it begins to degenerate unless fertilized.

The Uterus Is the Site of Development

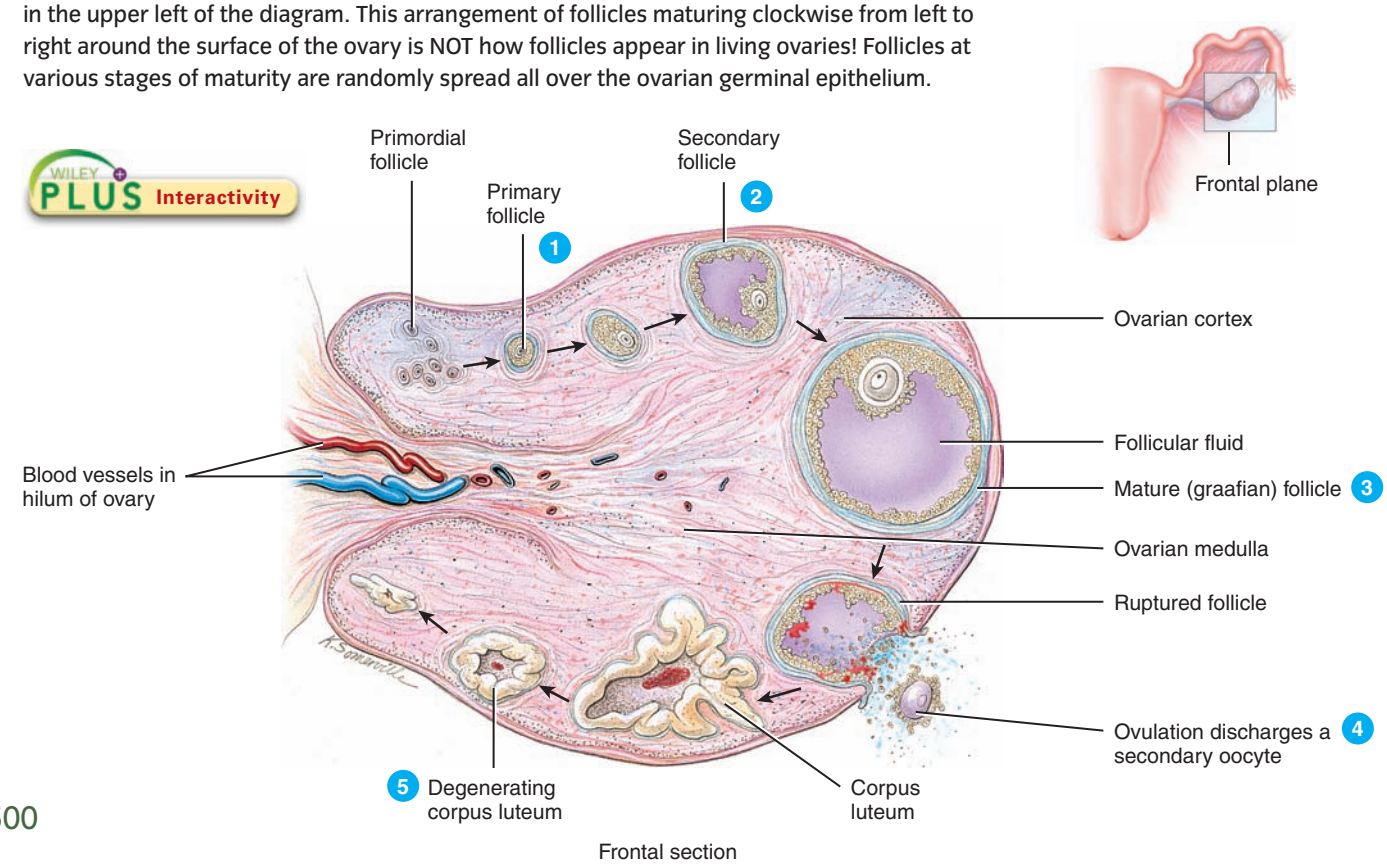
The uterus is the womb where fetal development occurs. This organ has an outer covering, the **perimetrium**, a middle layer of smooth muscle, the **myometrium**, and an inner **endometrium**, as seen in Figure 18.13. The endometrial lin-

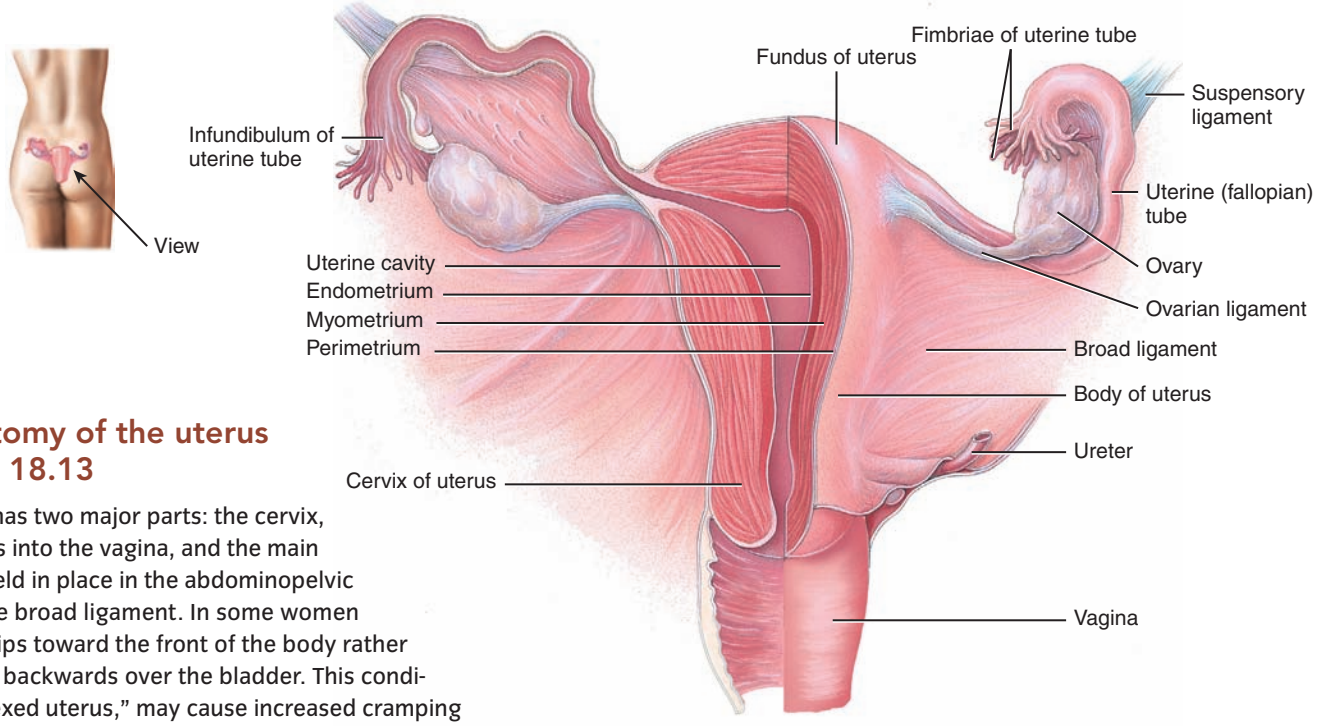
PROCESS DIAGRAM

THE PLANNER

The development of the follicle in the ovary • Figure 18.12

The follicles on the ovary are shown here in clockwise order, with the least mature follicles in the upper left of the diagram. This arrangement of follicles maturing clockwise from left to right around the surface of the ovary is NOT how follicles appear in living ovaries! Follicles at various stages of maturity are randomly spread all over the ovarian germinal epithelium.





Posterior view of uterus and associated structures

The anatomy of the uterus • Figure 18.13

The uterus has two major parts: the cervix, which opens into the vagina, and the main body. It is held in place in the abdominopelvic cavity by the broad ligament. In some women the uterus tips toward the front of the body rather than flexing backwards over the bladder. This condition, a "reflexed uterus," may cause increased cramping at times in the female cycle.

ing thickens and sheds every 28 days or so in response to hormone levels, resulting in the menstrual flow. **Implantation** of the embryo occurs in the endometrial lining, which is built up every month in anticipation of receiving an embryo. If there is no successful fertilization, the endometrial lining is shed, resulting in most of the menstrual flow.

implantation Anchoring and settling of the embryo into the endometrial wall, starting placental formation.

cervix Base of the uterus.

The cells that line the **cervix** produce a mucus that aids fertilization. During ovulation, the cervical mucus is thin and watery, allowing sperm to enter the uterus. The mucus also becomes more alkaline, improving sperm survival in the usually hostile acidic environment of the vagina. When no egg is present, the cervical mucus is thick and inhospitable to sperm, forming a cervical mucus plug.

Pregnancy is a phenomenally intricate process. Fertilization must occur within a specified window of time, and implantation must then precisely follow. To implant, the developing embryo must land on receptive endometrial tissue and then digest its way into the tissue and start to form the placental tissues.

In healthy females, endometrial tissue occurs only within the walls of the uterus. However, in **endometriosis**, it also appears in the uterine tubes, on the external upper surface of the uterus, and even on the external surfaces of the urinary bladder and other pelvic organs. Trouble results during menstruation when the endometrial lining is shed, since the endometrial tissue is trapped inside the abdominal cavity rather than able to leave via the vagina. This misplaced tissue can also cause abdominal cramps or pain as it grows.

Because the uterine tubes do not touch the ovaries, each ovulated egg floats in the abdominal cavity, hopefully swept into the uterine tubes by the fimbriae. Fertilization can occur outside the uterine tubes if sperm are present in the abdominopelvic cavity when the ovum is released. If endometrial tissue is present, this developing embryo can implant on the superior surface of the uterus or bladder. Equally alarming, the embryo could be swept into the uterine tubes and implanted on endometrial tissue on the walls of the tube. **Ectopic pregnancies** occur whenever implantation occurs outside the uterus. In all cases, the embryo will not survive. If the implantation occurs in the uterine tubes, the life of the mother is also in jeopardy. The tubes cannot expand to accommodate the developing embryo. As the embryo grows and the tube is stretched, the mother will feel pain, and if she does not get medical assistance, the tube will rupture, causing internal bleeding and perhaps death.

Some women develop uterine problems. Some women past reproductive age develop uterine health problems, such as excessive bleeding related to the uterus or uterine cancer. One of the options they are given is to undergo a **hysterectomy**. The suffix *ectomy* means to excise or remove a gland or organ. Hysterectomy means to remove the "hyster," which derives from the Greek for "womb." What other words are rooted in *hyster*? Hysteria. Histrionics. These describe irrational behavior. Amazingly, it was once thought that the uterus was the root of this type of behavior, as it seemed that women suffered from more psychological disturbances than men. The root *hyster* is still used to refer to the womb in medical terminology, even though the womb, or uterus, is not related to hysteria.

A hysterectomy, the removal of the uterus, is performed when uterine or ovarian cancer is detected or as an emergency surgery to stop uterine hemorrhage. An elective hysterectomy can be used to alleviate difficult menstrual cycles. Severe cramping, bleeding, and other menstrual discomfort are eliminated with removal of the uterus. Fibroids, or benign tumors of the uterus, can also cause severe discomfort and excessive bleeding each month. If fibroids become troublesome, a hysterectomy is often recommended. Other reasons for electing a hysterectomy include endometriosis and uterine **prolapse**, which sometimes occurs in older women, usually after they have had children. The entire uterus drops slightly in the pelvic cavity, as the vaginal supporting ligaments sag. The bladder and rectum may be drawn down, causing discomfort and even displacement of these organs.

prolapse The dropping, sliding, or falling of an organ from its original position.

Hysterectomies prevent hormone production. Uterine and ovarian cancers are common pathologies that often lead to the recommendation of a hysterectomy. In these cases, both the uterus and the ovaries are removed. The hormones produced by the ovaries may stimulate cancerous growth, so it is wise to remove them from patients suffering uterine cancer, even if ovaries are healthy. If the patient suffers from endometriosis, the same principle holds. The ovaries are removed along with the uterus to prevent the misplaced endometrial tissue from responding to estrogens and progesterone. After the ovaries are removed, hormone replacement therapy is usually recommended to prevent postmenopausal symptoms, such as night sweats, mood swings, and loss of bone density.

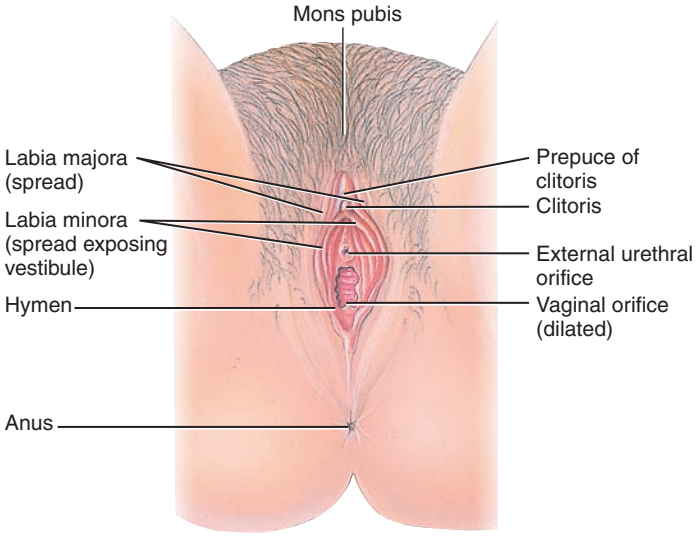
The Vagina, Vulva, and Many Glands Complete the Female Reproductive System

The vagina connects the uterus with the external environment, serving as the receptacle for the penis during intercourse, an outlet for monthly menstrual flow, and the birth canal through which the developed fetus leaves the uterus. This 10-cm-long muscular tube is lined with a mucous membrane. Because this tube must expand with the passage of the fetus, the walls feature transverse folds. The cells have a large store of glycogen, which breaks down to produce acids that retard microbial growth. Unfortunately, these acids are inhospitable to sperm as well and will kill them unless buffered. The aforementioned changes in cervical mucus during ovulation, together with the seminal vesicle fluids added to the semen, help sperm to survive and reach the egg.

External genitals are called the vulva. The external genitalia of the female are collectively called the **vulva**, as shown in Figure 18.14. The most sensitive area of the female external genitalia is the **clitoris**. This small tuft of erectile tissue is homologous to the glans penis in males. It is extremely sensitive and plays a role in sexual stimulation.

Female external genitalia • Figure 18.14

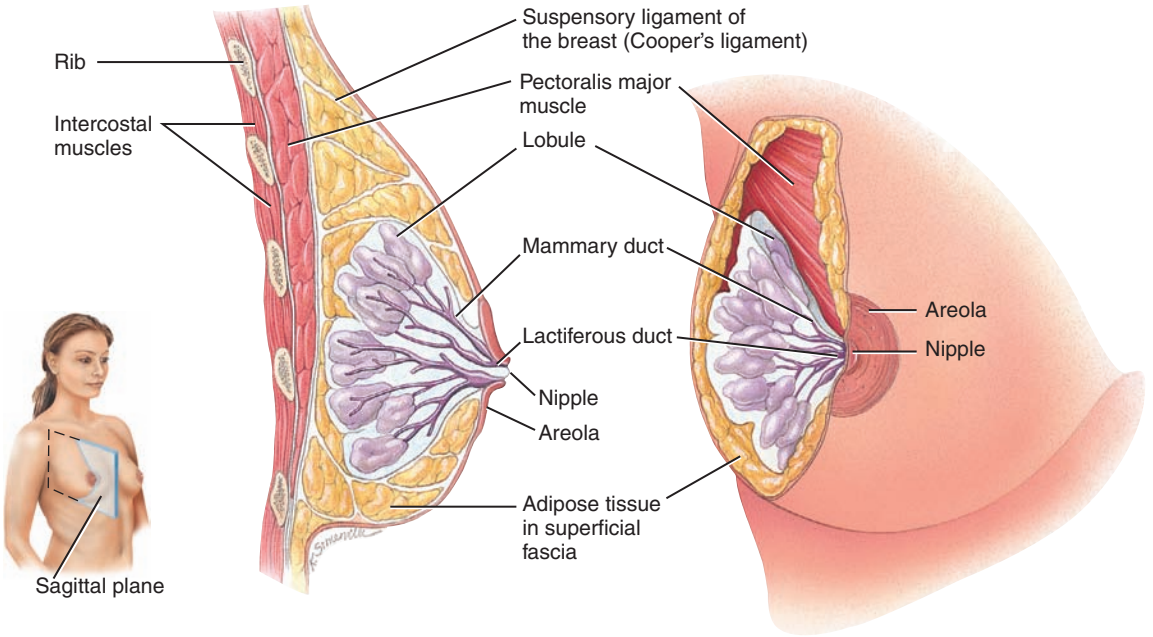
Note that the external urethral orifice is located between the clitoris and the vaginal orifice—but that in the female the urinary and reproductive systems are entirely separated from one another. The hymen (named after the Greek god of marriage) is part of the external genitalia—not part of the vagina—and is a thin fold of mucous membrane that partially covers or surrounds the vaginal orifice. The hymen is usually torn by physical activity, especially sexual intercourse.



Inferior view

Mammary glands • Figure 18.15

Since mammary glands are modified sweat glands, they are actually part of the integumentary system, or skin. However, unlike other sweat glands, the cells of these glands respond to estrogen and prolactin, depositing subcutaneous fat, enlarging the duct system, and producing milk rather than sweat.



a. Sagittal section **b.** Anterior view, partially sectioned

The mammary glands are modified sweat glands. The mammary glands are actually modified sweat glands located above the **pectoralis major** muscles. See Figure 18.15. These glands are supported by ligaments and are protected by a layer of adipose tissue. They are composed of **lactiferous** ducts, connected to lactiferous sinuses. Milk is produced in the lobules of the gland, stored in the lactiferous sinuses, and passed out of the breast via the lactiferous ducts. Naturally, this function is necessary only after childbirth. The breasts swell during the last weeks of pregnancy in response to the hormone **prolactin** (PRL) made by the anterior pituitary gland. Once milk is formed, it is released from the gland in response to **oxytocin**.

lactiferous
Producing milk.

Oxytocin is released from the posterior pituitary gland when an infant suckles, in the "let-down" reflex. This response can also occur when the mother hears her baby cry or even thinks about nursing her baby.

The Female Orgasm Is an Emotional and Physiological Epiphany

We have seen that female and male sexual responses share some similarities, as illustrated in Figure 18.7. In both sexes, blood flow to the genitals is altered, gland secretion increases, and orgasm results in rhythmic contractions of pelvic muscles. During arousal for a female, blood flow to the clitoris is altered, glands begin to secrete lubricating fluids, and heart rate and blood pressure increase. Again, arousal is governed by the parasympathetic nervous system. This phase is highly responsive to sensory stimulation, such as touching of the genitals, breasts, lips, or earlobes. Other sensory stimulation, including visual, auditory, or even olfactory stimuli, can increase or dampen the arousal.

As excitement builds, a plateau is reached. This can last from a few seconds to many minutes. During this phase many females experience a rash-like flush to the skin of the upper neck and face. Orgasm begins a series of wave-like muscular contractions, and an intense pleasurable sensation marks the end of the plateau. As with the male, orgasm and resolution are controlled by the sympathetic nervous system. In the female, receiving the male ejaculate does not provide much stimulation. Simultaneous orgasm is not automatic, nor should it be expected. Females do not require a refractory period and can experience two or more orgasms in rapid succession.

The resolution phase begins with a sense of relaxation. Heart rate, blood pressure, and blood flow all return to prearousal levels. Resolution time is variable, taking longer to arrive when no orgasm occurred.

Two Hormonal Cycles Occur at Once in Females

The female reproductive cycle is a study in feedback controls. Two separate cycles are occurring at once in the nonpregnant female: the **ovarian cycle** and the **uterine cycle**. Each affects the other, and together they cause the cyclic menstrual flow of the postpubescent female.

The ovarian cycle is a programmed series of events that occur in the ovary as eggs mature and ovulate, governed by hormones from the anterior pituitary gland. Hormones released from the ovary, in turn, affect the endometrium of the uterus. Ovarian hormones cause the uterine cycle, which in turn is responsible for the appearance of the **menstrual flow**. The term **female reproductive cycle** usually includes both the ovarian and uterine cycles, as well as the hormones that regulate them and the associated cyclic changes in the breasts and cervix. Figure 18.16 shows both cycles.

PROCESS DIAGRAM

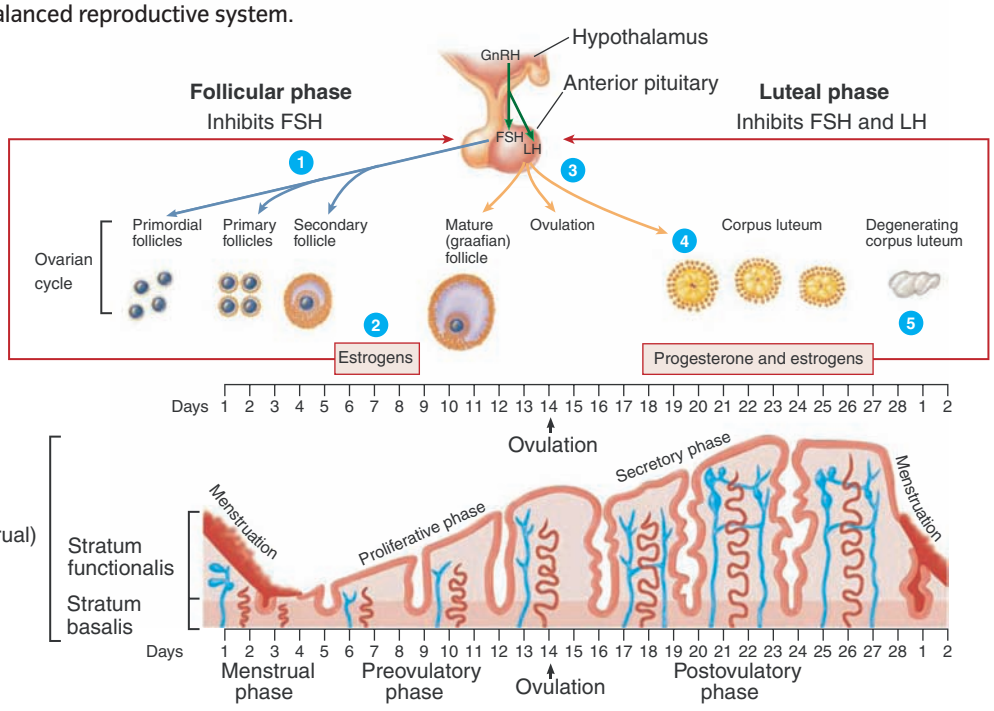
Female reproductive cycle • Figure 18.16

THE PLANNER

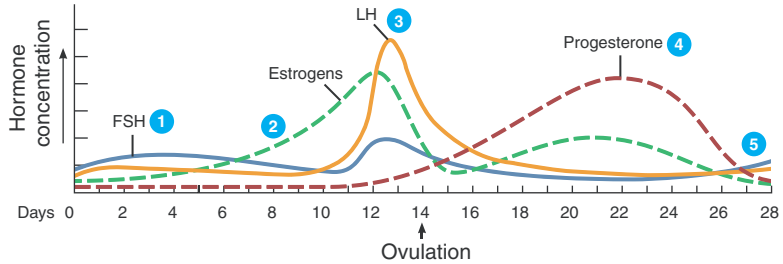
WILEY PLUS Interactivity

The female reproductive cycle is actually two cycles operating in tandem. The anterior pituitary secretes hormones that cause changes in the ovary, and the ovary releases hormones that cause changes in the uterine lining. Negative feedback systems operate in both cycles to maintain a balanced reproductive system.

1. FSH is released from the anterior pituitary gland, stimulating development of ovarian follicles.
2. Estrogens are released from developing ovarian follicles, causing buildup of the uterine lining.
3. When estrogen levels reach a peak, the anterior pituitary gland releases LH. LH causes ovulation.
4. Ovulation stimulates the production of progesterone from the follicular cells remaining in the ovary. Progesterone causes the formation and functioning of uterine glands.
5. After 14 days, the ovary ceases production of progesterones. Blood hormone levels decline, causing the uterine lining to slough off. When blood hormone levels are low, FSH is again secreted from the anterior pituitary gland.



a. Hormonal regulation of changes in the ovary and uterus

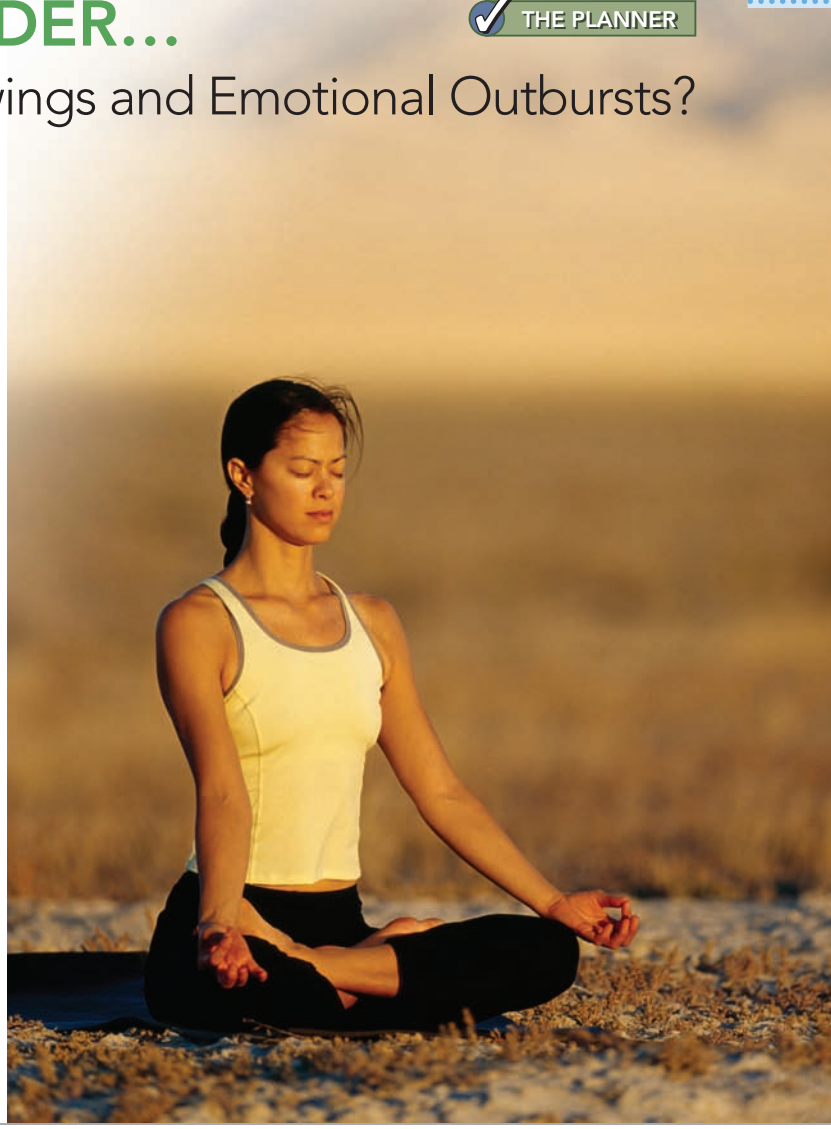


b. Changes in concentration of anterior pituitary and ovarian hormones

I WONDER...

THE PLANNER

Can PMS Really Cause Mood Swings and Emotional Outbursts?



What is the science behind the sensational stories of crazy women? Can PMS really cause mood swings and emotional outbursts? Premenstrual syndrome (PMS) is a cyclical disorder of severe physical and emotional distress that appears during the postovulatory phase of the female reproductive cycle and disappears when menstruation begins.

A severe form of PMS, called premenstrual dysphoric disorder (PMDD), describes as many as 150 physical and emotional symptoms that are linked to the menstrual cycle. Common symptoms include nausea and acne. Breast tenderness and swelling may also occur and are linked to fluid retention. Some symptoms are psychological, including severe mood swings, anxiety, and depression. Although as many as 80% of American women may have some of these symptoms during their reproductive years, PMDD itself affects only 8 to 20%.

Women with severe cases of PMDD often have high blood levels of two stress hormones, cortisol and norepinephrine. That's significant, because scientists link many of the symptoms of PMDD to the interaction of hormones and the brain. Just as the brain (acting through its control of the hypothalamus gland) can regulate hormones, hormones can affect the brain, as we see in the way that estrogen and testosterone can stimulate sexual arousal. However, stress, lack of exercise, poor diet, tobacco, alcohol, and caffeine all aggravate PMDD symptoms.

Medicine, including anti-anxiety medications, can be prescribed for severe symptoms, yet many women can moderate their symptoms through behavior or diet. Calcium supplements and stress reduction techniques, such as exercise, yoga, and breathing exercises can help. If you or someone you love suffers from PMDD, it is important to be supportive and to seek medical assistance.

The female reproductive cycle is ultimately regulated by **GnRH** (gonadotropin-releasing hormone) from the hypothalamus. Through its effects, FSH and LH are produced in the anterior pituitary. Follicle-stimulating hormone (FSH) stimulates follicle cell growth in the ovaries, maturing the follicles and associated ova, hence the name. Luteinizing hormone (LH) causes the most mature follicle to burst (ovulate), leaving a yellow body of spent follicular cells (**corpus luteum**) on the ovary.

The maturing follicle cells secrete estrogen into the bloodstream. Estrogen stimulates the development of the female secondary sex characteristics, including adipose deposition in the breasts, hips, and abdomen, and the development of groin and axillary hair. Estrogen also increases protein buildup, working in harmony with human growth hormone to increase body mass. In addition, estrogen lowers blood cholesterol. This hormone has been implicated in PMS, the mood swings associated with the days immediately prior to beginning a new menstrual cycle. Investigate the truth of these accusations in *I Wonder… Can PMS Really Cause Mood Swings and Emotional Outbursts?* In the blood, estrogen serves as a feedback mechanism inhibiting the production of GnRH, FSH, and LH. As the estrogen level increases, GnRH, FSH, and LH levels all drop. Inhibin is also secreted by the cells of the growing follicle as well as the corpus luteum. Inhibin prevents secretion of FSH and LH, adding another level of feedback to the system.

Once the corpus luteum has been formed, it begins to secrete **progesterone**, which stimulates the growth of, and glandular secretion in, the endometrium. As the uterine lining thickens, the uterine glands begin to function. The corpus luteum also secretes small quantities of **relaxin**, a hormone that quiets smooth muscle. It is thought that relaxin aids in implantation. Perhaps implantation is more likely to be successful in a relaxed and quiet uterus. Production of relaxin increases dramatically if implantation occurs, as the placenta begins secreting large quantities. A less irritable uterus provides a better environment for the developing embryo and permits placental development.

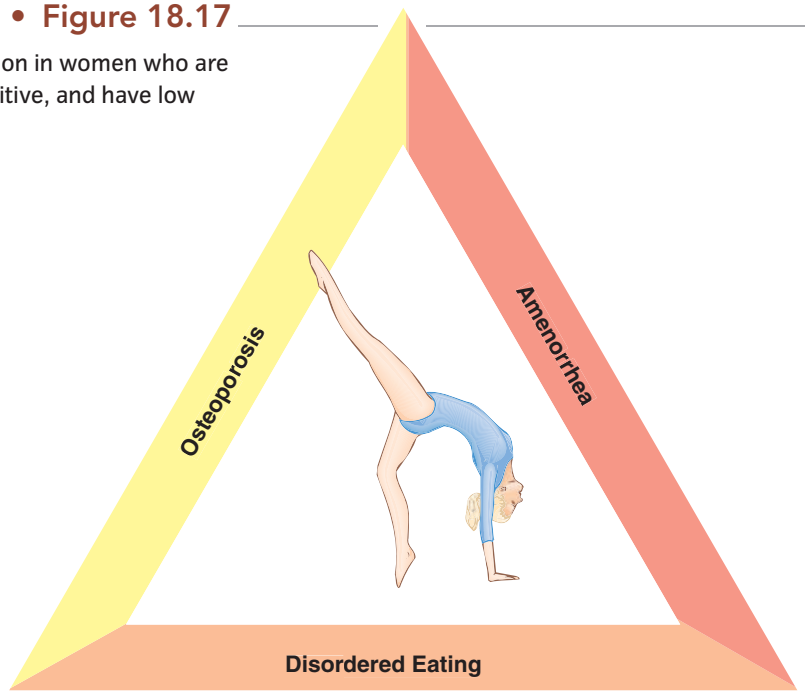
Physiological and Hormonal Changes Are Part of an Integrated System

The physiological changes in the ovaries and uterus and the hormonal changes during the female reproductive cycle are part of an integrated system.

1. The uterine cycle is the regular growth and loss of the endometrial lining. At the beginning of the cycle, the month-old lining is shed. This usually takes from three to seven days to complete, allowing the female to know precisely when her "period," or menstrual flow, began. The low levels of all female hormones in the blood impair blood flow to the outer layer of the endometrium, causing the lining to slough off. The volume of a typical menstrual flow is approximately 50 to 150 ml, made up of tissue fluid, mucus, blood, and epithelial cells.
2. The next 6 to 13 days make up the **preovulatory phase**. The variable length accounts for the individual differences in menstrual cycles. FSH secretion increases, stimulating follicles in the ovary and causing maturation of approximately 20 follicles. By day 6, one follicle in one ovary has grown faster than the others, becoming the dominant follicle. This follicle secretes estrogen and inhibin, preventing further release of FSH and therefore quieting the development of the remaining follicles in both ovaries.
3. The dominant follicle will enlarge until it appears as a swollen area on the surface of the ovary. This graafian follicle increases estrogen production under the influence of LH from the anterior pituitary. This stage of ovarian activity is called the **follicular phase** due to the involvement of the follicle cells.
4. An increased estrogen level in the blood repairs blood vessels damaged during the previous menstrual flow and stimulates mitosis of the endometrial cells. Glands develop in the innermost layer of the endometrium, but they do not yet function. Because the endometrium is growing (proliferating), this is called the **proliferative phase**.
5. Increasing levels of estrogen stimulate increased production of GnRH, which in turn stimulates a surge in LH. The graafian follicle reacts to this LH spike by popping, extruding fluid and the ovum into the abdominopelvic cavity. This violent, often painful action is **ovulation**. A slight temperature increase indicates that ovulation has taken place. This normal response to trauma is the basis of some natural birth control methods, such as the sympto-thermal method, that involve charting body temperature every morning. A slight spike in recorded temperature indicates ovulation, when an ovum is released and made available for fertilization.
6. After ovulation, the follicle cells are dormant and the corpus luteum cells begin to function. This **postovulatory phase** has the most uniform duration, taking 14 days in almost every woman. The corpus luteum formed during ovulation will survive for exactly 14 days. If no fertilization occurs, the corpus luteum degenerates. During the life span of the corpus luteum, the progesterone level increases. As it degenerates, progesterone declines.
7. In the uterus, the endometrial lining is maintained by progesterone. The endometrial glands begin to function, and the lining is prepared for a possible implantation. This phase is often called the **secretory phase** in reference to these glandular activities. Assuming there is no implantation and no pregnancy, progesterone, estrogen, and inhibin levels all drop by the end of the postovulatory phase. As the progesterone levels decline, the endometrial lining loosens. With such low hormone levels in the blood, the endometrial lining cannot be maintained and is lost from the underlying tissues, and menstruation begins again.

Female athlete triad • Figure 18.17

This syndrome is more common in women who are perfectionists, highly competitive, and have low self-esteem.



Lifestyle Has an Effect on the Female Reproductive Cycle

Correct functioning of the female reproductive cycle depends on many variables. Lifestyle has a profound effect, as can be seen in postpubescent elite female athletes. True, girls who participate in sports are healthier, get better grades, and are less likely to suffer depression or use illegal substances. However, intense involvement in sports can be risky. The **female athlete triad** is a condition in which health deteriorates due to overemphasis on sports, as seen in Figure 18.17. Three related problems may arise: disordered eating, **amenorrhea** (lack of a menstrual cycle), and osteoporosis.

Often, coaches or others involved in girls' sports inadvertently feed into this triad by emphasizing intense training and success at all costs. Many female athletes are told to focus on their diet and weight, but if this focus is mainly on avoiding weight gain rather than quality of nutrition, it can contribute to eating disorders. Continued intense exercise and caloric restrictions can also interfere with a girl's reproductive cycle. It takes a fair amount of energy to sustain reproductive ability, and low caloric intake and increased muscular activity may make the necessary energy simply unavailable. Estrogen production slows, causing irregular menstrual cycles or ending them entirely, contributing to postmenopausal symptoms. A declining estrogen level reduces bone density, which is especially troublesome in teenagers, when the skeleton reaches its densest condition, forming a strong foundation for adult life. Some teenage female athletes can have a bone density typical of a 60-year-old woman, and training can lead to stress fractures and broken bones.

CONCEPT CHECK STOP

1. **What** are the female reproductive organs and **what** is the function of each?
2. **How** does oogenesis differ from spermatogenesis?
3. **What** are the hormones associated with female reproduction and **what** are the functions of each?

18.4 There Are Many Birth Control Choices

LEARNING OBJECTIVES

1. **Discuss** the different types of birth control.
2. **Describe** the benefits and risks of each form of birth control

Although the biological function of the reproductive system is to propagate the species, pregnancy is not always the desired outcome of sexual activity. Preventing pregnancy is important to many couples, and there are now many good options that can fit just about anyone's lifestyle. Of course, the only absolute method of birth control is **abstinence**. If no sperm enters the female, pregnancy is impossible. Other birth control methods rely on **surgery**, **hormones**, **IUDs**, **spermicides**, **barriers**, or **behavior modification**. Each form of birth control has advantages and disadvantages, as seen in Table 18.1, and choosing the optimum method can be confusing. The choice should be made after studying information on each form and considering the risks. It is also helpful to discuss the various methods with your partner. A birth control method that does not complement your lifestyle is likely to be less effective than one you can follow without changing your routine.

Failure rates of birth control methods **Table 18.1**

Method	Failure rates* Perfect use†	Typical use
None	85%	85%
Complete abstinence	0%	0%
Surgical sterilization		
Vasectomy	0.10%	0.15%
Tubal ligation	0.5%	0.5%
Hormonal methods		
Oral contraceptives	0.1%	3%‡
Depo-provera	0.05%	0.05%
Intrauterine device		
Copper T 380A	0.6%	0.8%
Spermicides	6%	26%‡
Barrier methods		
Male condom	3%	14%‡
Female condom	5%	21%‡
Diaphragm	6%	20%‡
Periodic abstinence		
Rhythm	9%	25%‡
Sympto-thermal	2%	20%‡

* Defined as the percentage of women having an unintended pregnancy during the first year of use.
† Failure rate when the method is used correctly and consistently.
‡ Includes couples who forgot to use the method.

Birth Control Can Be Handled Surgically

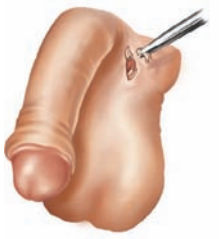
Surgical sterilization can prevent gametes from meeting. Figure 18.18 shows both female and male sterilization procedures. In either gender, the tube through which sperm travels to reach the egg can be blocked, preventing fertilization.

Vasectomies prevent sperm from leaving the epididymus. Male sterilization is an easy outpatient surgery that requires no scalpels and only two small punc-

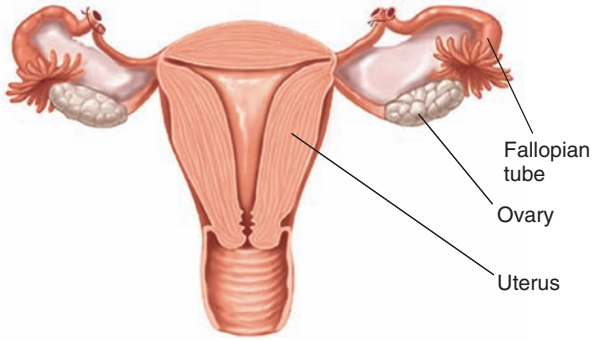
Surgical sterilization • Figure 18.18

The medical term for a vasectomy is "deferentectomy," since the medical term for "vas deferens" is "ductus deferens." Two more radical surgical sterilization procedures are not shown: hysterectomy (removal of the uterus) and castration (removal of the testes).

In a vasectomy, a small section of the vas deferens is removed and the ends are tied.



In a tubal ligation, the uterine tubes are cut and tied.



tures at the posterior base of the scrotal sac near the body. The spermatic cord is located; the vas deferens isolated, pulled out slightly, and closed either by looping and **ligating**, by cutting and sealing, or by clamping. The skin of the scrotal sac is closed without stitches, and that's that. A local anesthetic prevents pain during the puncturing, and the patient may feel a slight pulling as the vas deferens is located and pulled through the skin. Testosterone levels are not affected, so sexual desire does not change. Because the sperm contribute very little to the total volume of semen, a vasectomy is virtually undetectable in sexual performance.

ligating Tying off a tube to close it.

After vasectomy, sperm in the seminiferous tubules cannot pass the vas deferens to reach the seminal vesicles. During ejaculation, sperm is forced from the epididymus to the blockage in the vas deferens and stops. The muscular contractions of the orgasm continue to push through the male system, causing the release of fluid from the seminal vesicles, the prostate, and the bulbourethral glands. Since there may be sperm in the vas deferens above the vasectomy, sterility may be delayed for up to six weeks while any remaining sperm leave the system. After that, the male should be 100% sterile. This procedure costs between $500 and $1,000 and is covered by most insurance companies. As with any medical procedure, complications can arise, but the procedure is less risky than sterilization for females.

Tubal ligation blocks the uterine tubes. The female equivalent of a vasectomy is a **tubal ligation**, which blocks the uterine tubes to prevent both the egg from reaching the uterus and the sperm from passing through the uterine tubes to an awaiting ovulated egg. Tubal ligation requires a brief stay in the hospital. The woman is anesthetized, her abdomen is distended with CO_2 gas to separate her organs, and the two uterine tubes are located via **laparoscopy**. The tubes can then be cut and tied similar to the vasectomy, sealed via electrocautery, or closed with titanium clamps. Alternatively, small coils called microinserts can be placed in the uterine tubes. These coils are brought in through the cervix and placed in the first third of the uterine tube, where they irritate the tube and cause scar tissue to form. After approximately three months, the scar tissue will block the uterine tube, preventing the passage of egg or sperm. Although not technically a tubal ligation, these microinserts produce the same result.

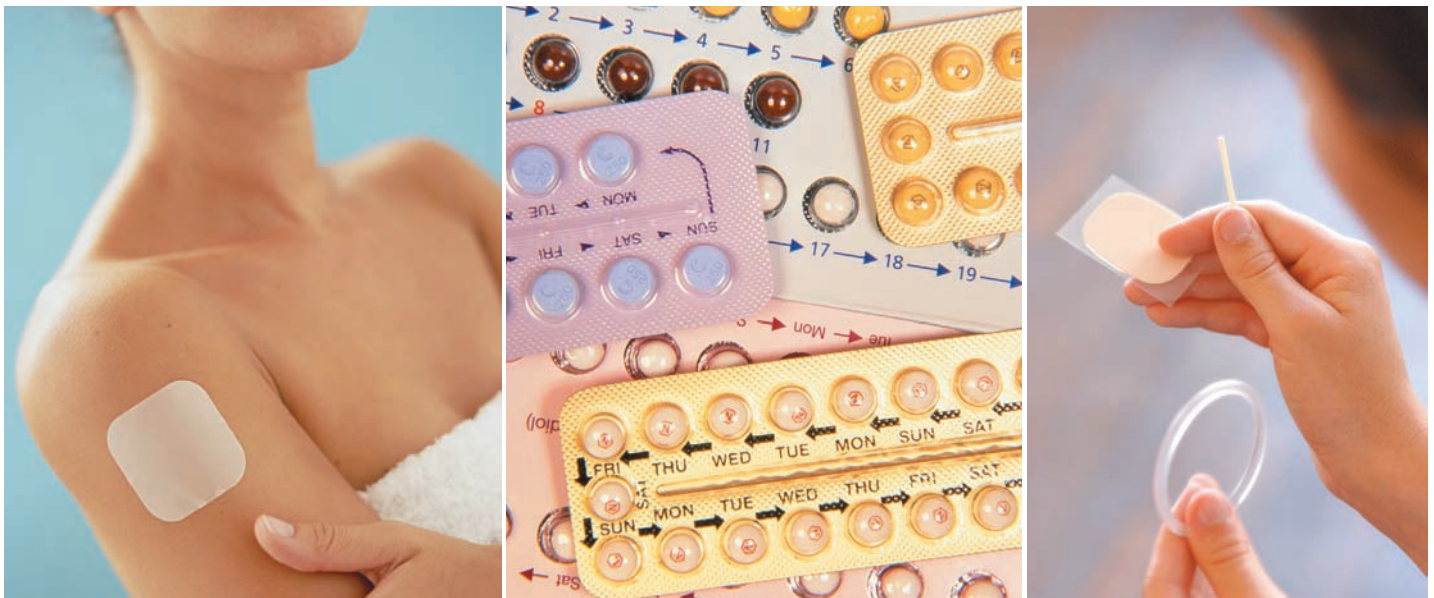
laparoscopy Noninvasive surgery using fiber-optic cables, remote control, and tiny surgical tools.

Hormonal Methods of Birth Control Are Another Option

Whereas surgery is permanent, hormonal methods, as seen in **Figure 18.19**, are temporary—delivered in pill or patch form. The birth control pill is an **oral contraceptive**, a combination of synthetic estrogens and progestins that alters the natural hormonal rhythms of the female. The birth control patch is a similar mixture of hormones absorbed through the skin rather than through the digestive membranes. In both cases, keeping estrogen and

Some hormonal birth control options • Figure 18.19

Many women opt for "the pill," as this is an easy way to control their reproductive cycle, does not require surgery, and can be stopped at any time. As medical research moves forward, the side effects of the pill continue to diminish. Other hormonal options include Norplant®, the vaginal ring, and birth control patches.



progestin levels high inhibits the secretion of FSH and LH from the anterior pituitary gland. Without FSH, the follicles in the ovaries do not mature, and no eggs are ready to ovulate. The hormone levels created by birth control pills almost guarantee that natural production of estrogen remains low, LH is not produced, and ovulation will not occur. Even birth control pills that maintain a very low estrogen level to alleviate side effects do not cut out the hormone entirely.

Some birth control pills also alter mucus production of the cervix, creating an environment inhospitable to sperm. Taken correctly, the pill is close to 100% effective. However, missing one dose can cause a dip in the artificial hormone levels, allowing natural rhythms to resume. By artificially regulating the menstrual cycle, the pill also provides beneficial side effects, such as scant periods, a regulated and predictable menstrual cycle, and protection against endometriosis, breast cancer, and ovarian cancer.

Because some women prefer not to have a menstrual period at all, there is now a form of birth control pill that provides three months of continuous hormonal control, rather than the usual three weeks of control and one week of placebo pills. This new form permits menstruation only four times a year. There has been little research to date on the side effects of this dosage of hormones. See *Health, Wellness, and Disease: Hormonal Controls: The Good, the Bad, and the Ugly* for more information.

There are alternative forms of hormonal birth control. **Norplant**, **Depo-provera**, and the **vaginal ring** are alternative forms of hormonal contraception. Norplant is a series of six hormone "sticks" surgically implanted under the skin of the upper arm. These sticks slowly leak progestins into the female system for five years, inhibiting ovulation and causing thickening of the cervical mucus. If the Norplant sticks are removed, fertility is restored. Depo-provera is an intramuscular injection of progestin given every three months. The initial months using Depo-provera can be difficult, as the body adjusts to the changes initiated by the progestins. Some women experience weight gain, PMS-type symptoms, fluid shifts, and inconsistent spotting and cramping. As another hormonal alternative, the vaginal ring is worn in the vagina for three weeks. It slowly releases estrogen and progestins in levels similar to the oral contraceptives discussed above. Removing the vaginal ring every fourth week allows the slight increase in endometrium to be shed, similar to a normal menstrual flow.

Hormones can be used to prevent implantation. Emergency contraception, sometimes referred to as the "**morning after**" pill, prevents implantation of the fertilized ovum or causes an already implanted embryo to be lost as the endometrial lining weakens. The term *"morning after"* is misleading, for this form of birth control may be carried out within three days to seven weeks of unprotected sex. Emergency contraception can only be obtained with a prescription and may cause serious cramping and discomfort. This contraceptive method works similarly to the pill in that it requires altering the hormonal environment of the female. Two types of emergency contraception are available currently. Preven® is the brand name for a series of four pills, two to be taken within 72 hours of unprotected sex and two more to be taken 12 hours later. These pills cause the lining of the uterus to become inhospitable to implantation. The other form of emergency contraception is the drug mifepristone, or RU-486. It works by decreasing the uterine cells' sensitivity to progesterone. This in turn causes the uterine lining to be shed, just as it is at the end of a normal uterine cycle. Mifepristone essentially causes a chemical abortion of an implanted embryo. See *Ethics and Issues: RU-486: A Chemical Abortion Fraught with Issues* on page 512 for more on this method.

Elective Abortion Can Take Several Forms

Elective abortion, or more commonly simply "abortion," is the termination of a pregnancy. Whereas early-stage pregnancy can be terminated using mifepristone, abortions are performed in medical offices, hospitals, or clinics. Elective abortions are performed only in the first trimester of pregnancy and can take one of several forms. The uterus can be scraped clean, removing the endometrial lining as well as the implanted embryo, the contents of the uterus can be suctioned out, or a strong saline solution can be injected into the womb, causing loss of the endometrial lining. Abortions are performed for many reasons, including a

elective abortion Removal of the developing embryo initiated by personal choice.

HEALTH, WELLNESS, AND DISEASE

Hormonal Controls: The Good, the Bad, and the Ugly

THE PLANNER

When the pill first became available in the 1960s, it was seen by many as a ticket to sexual freedom. In 1957, G. D. Searle and Company produced and marketed Enovid, a combined oral contraceptive pill in the United States. It was originally prescribed as a treatment for menstrual cycle disorders, but in 1960 the USFDA approved its use for contraception. Used properly, it prevented pregnancy 99.9% of the time. This was seen as a good thing, and remains one of the most compelling reasons to "go on the pill." With the good, however, came some bad. Although effective, Enovid was discontinued in 1988, due to the health risks associated with its high estrogen content. Enovid contained 150 µg of mestranol, an estrogen derivative, and slightly more than 9.5 mg of norethynodrel, a synthetic progestin. Scientists discovered that high levels of estrogen in the female bloodstream might cause blood clot formation, which can lead to stroke or heart attack, breast cancer, cervical cancer, or benign liver tumors. Additionally, many of the symptoms of menopause, such as hot flashes, moodiness, and loss of cognitive functioning, are due to high estrogen levels in the blood. Women taking the pill to prevent pregnancy often found themselves suffering from blood clots or even stroke. This was not only bad, it was downright ugly!

The main difference between the hormonal birth control pills offered today and those produced in the 1960s is the level of hormone. The estrogen levels in current birth control pills range from a low of 20 µg to a high of 50 µg. The progestin levels are also significantly reduced, averaging only 1 mg. This has alleviated most of the negative side effects of the past.

Additionally, the pills are now made using ethinyl estradiol as the estrogen component, and any one of seven different progestin derivatives. Using only one type of estrogen in all contraceptive pills helps physicians decide which pill will be most effective for each patient. The estrogen effects can be manipulated easily and predictably by changing the dosage, and pairing it with different progestins then allows physicians to fine-tune the side effects of the pill. Each type of progestin offers slightly different benefits and drawbacks. Some increase the androgenic hormonal effects in women prone to such development (increased hair production, increased probability of developing acne) while others aid in menstrual flow regulation.

ETHICS AND ISSUES

THE PLANNER

RU-486: A Chemical Abortion Fraught with Issues

RU-486 is a synthetic steroid hormone that can have a profound effect on the production of certain other hormones. By blocking targets of sex hormones and certain other hormones, it acts as an antagonist to those hormones. It is, among other things, an anti-progesterone and anti-glucocorticoid that is actually a combination of two drugs that together induce uterine contractions and miscarriage. RU-486 is legal in the United States for use during the first trimester of pregnancy. Since its approval for use by the federal Food and Drug Administration in 2000, well over 500,000 pregnancies have been deliberately terminated chemically using RU-486 as an alternative to surgical abortion.

Abortion-rights advocates hope that use of RU-486 will allow women to induce a chemical abortion with privacy, under a doctor's supervision. Abortion-rights opponents say that the privacy that comes with RU-486 is a danger, since it can be done anywhere and by anyone.

Chemical abortion takes between ten days and two weeks. The first compound, mifepristone, is taken for three days, followed by a single administration of misoprostol. Over the next few days, the drugs combine to dislodge the fetus from the uterine wall, induce uterine contractions, and ultimately expel the fetus.

RU-486 should not be confused with "Plan B®," a high-dose, progestin-only contraceptive, and other so-called "morning-after" or emergency contraceptive pills. When taken within 72 hours of unprotected sex, emergency contraceptives act not to inhibit conception, but rather to inhibit a fertilized egg from implanting in the uterine wall. This, say anti-abortion advocates, means that emergency contraception is an abortifacient, not a contraceptive. Fertility experts disagree, arguing that a high percentage of fertilized eggs do not implant for many different reasons, and therefore pregnancy does not truly occur until the embryo implants.

Critical Reasoning Issues Fertility, pregnancy, and abortion are issues fraught with moral, ethical, and religious conflict. So-called "conscience" legislation has been passed in some states. Some conscience legislation allows a pharmacist to refuse to fill prescriptions for RU-486 or emergency contraceptives if it is against his or her personal beliefs, despite the fact that both are legal, and despite the conditions of pharmacists' licenses that they fill all lawfully written prescriptions.

Think Critically

1. Should pharmacists be able to "opt out" of providing services because of personal belief?
2. If you believe they may opt out, should they be required to let patients know of other pharmacists in the area who will fill the prescription?
3. Doctors and hospitals have also sought conscience legislation for themselves. Roman Catholic hospitals have asked state legislatures to not force them to administer emergency contraceptives to rape victims who are brought to their emergency departments. Doctors have sought conscience legislation to allow them to not have to administer emergency contraception to rape victims they may treat in any emergency room in which they work. Should Roman Catholic hospitals, or individual doctors working in non-Catholic hospitals, be able to "opt out" of treating rape victims with a legal and safe drug?

pregnancy resulting from rape or incest, a pregnancy that endangers the life of the mother, or life-threatening malformations of the fetus. Because the procedure removes a potentially viable fetus, there is much controversy surrounding abortion. Currently, most states in the United States allow elective abortion, but the issue does arise in courts periodically, and the ethical dilemma remains—life of the fetus versus the reproductive life of the mother.

The Intrauterine Device Provides an Obstruction to Conception

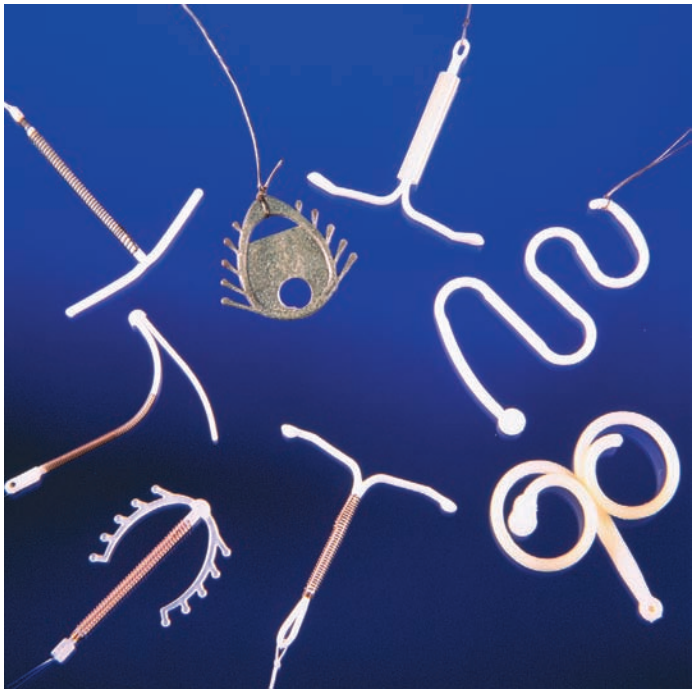
The **intrauterine device (IUD)** is a foreign object that floats in the uterus and periodically hits the endometrial lining, preventing implantation. Figure 18.20 shows some IUDs. Most IUDs are made of plastic or copper. They can be almost any shape from a squiggly S to a number 7 to a capital T. Each IUD has a string that hangs out of the cervix in order to allow removal. The most common IUD is the Copper T380A. This small copper wire is placed in the uterus. It may cause cramping and bleeding upon implant, but these symptoms usually subside. The IUD can remain in the uterus for up to ten years. IUDs that carry hormones further prevent implantation, but they must be replaced every five years.

IUDs lost popularity after the Dalkon Shield episode in the 1970s. This IUD was made of plastic, and looked like a bug with a rounded appearance and five leg-like structures extending from each side. Unlike other IUDs marketed with a single filament string extending from the cervix, this one had a larger, braided string. This large device was implicated in 12 deaths due to complications and infection allegedly introduced with the IUD. The thought was that the complicated string may have been a poor design, allowing bacteria to enter the braids and then enter the uterus. Test results did not confirm this theory, however. Despite no proof that the Dalkon Shield was responsible, plaintiffs won a lawsuit, the Shield was pulled from the market, and many people erroneously still think all IUDs are dangerous.

Spermicides Kill Sperm

Spermicides are creams and jellies that contain **nonoxynol 9**, a compound that kills sperm by disrupting the cell membrane. Recent evidence shows that nonoxynol 9 causes shedding of epithelial cells in alarmingly large sheets immediately after being introduced to the vagina. This loss of protective epithelium from the vagina or anal canal could allow entry of sexually transmitted diseases, trading one sexual problem for another. Spermicides are more effective when used in conjunction with a barrier method. See Figure 18.21 for examples of spermicides.

Intrauterine Device (IUDs) • Figure 18.20



Spermicides • Figure 18.21

A sampling of barrier methods • Figure 18.22

a. Latex condoms

b. Diaphragm

c. Cervical cap

Barrier Methods Block the Entry of Sperm; Some Protect Against STDs

Barrier methods of birth control establish a physical obstacle between sperm and egg. The **condom** is a barrier worn on the penis, whereas the **female condom**, **cervical cap**, and **diaphragm** are barriers worn in the vaginal area. Latex condoms are also effective against most STDs (Figure 18.22a). Natural condoms, made of lambskin, do not block STDs, but do provide a barrier against sperm. The pores in these condoms are too large to block bacteria or viruses.

The diaphragm is a rubber disc held in the vagina by a flexible ring (Figure 18.22b). A diaphragm blocks sperm but does not protect the vagina against STDs. A cervical cap is a smaller version of the diaphragm that is placed over the cervix (Figure 18.22c). To be effective, both devices must be fitted by a physician. The female condom is a hybrid of diaphragm and condom, composed of two flexible rings connected by a latex sheath. The upper ring functions as a diaphragm, while the lower ring holds the latex sheath against the walls of the vagina, providing protection from disease along the entire tract. Combining a spermicide with a barrier method provides much greater protection against both STDs and pregnancy.

The Rhythm Method Is Another Viable Technique

The female reproductive cycles provide clues about the timing of ovulation. If the female knows the exact timing of ovulation, she can avoid pregnancy by preventing the introduction of sperm into her reproductive tract during that time. Due to the timing of egg movement, the window of fertility is a six-day period beginning five days prior

Ovulation test kit • Figure 18.23

to ovulation and ending the day of ovulation. Test kits like the one shown in **Figure 18.23** are available to help predict the timing of ovulation. Self-monitoring, such as charting daily morning temperature or observing changes in cervical mucus, also gives a fairly accurate picture. By recording temperature or mucus condition on a calendar for a few months, the general ovulatory pattern becomes clear. This method, with temperature charts and precise information on when ovulation occurs, is referred to as the sympto-thermal method of birth control. The rhythm method of birth control follows a similar practice but does not include temperature as a cue to ovulation. Couples who follow the rhythm method rely on consistency in the female's menstrual cycle. Based on history, ovulation is predicted. Practicing abstinence during her six-day window of fertility greatly reduces the chance of pregnancy. The more accurate her observations, the less likely she is to become pregnant. Another behavioral method of birth control is the withdrawal method. In this method, the penis is removed from the vagina prior to ejaculation. This method is very risky because some fluids are released prior to the ejaculation. These fluids may contain sperm, which could fertilize any available egg. Of all methods, withdrawal is the least reliable, resulting in pregnancy far more often than other methods.

CONCEPT CHECK STOP

1. **What** are the different types of birth control and **how** do they work?
2. **What** are the benefits and risks of abstinence? Of hormonal methods of birth control? Of barrier methods?

18.5 Sexual Contact Carries a Danger: Sexually Transmitted Diseases

LEARNING OBJECTIVES

1. **List** the main categories of STD.
2. **Describe** the treatments for the most common STDs.
3. **Explain** why knowledge of STDs is important.

Sexual reproduction is critical to the survival of the species. During sexual reproduction, genes are mixed and recombined, adding variability to the human population.

For all of its benefits to the population, sexual reproduction carries a real danger to individuals: sexually transmitted diseases (STDs). These range in severity from a mild discomfort that can be cured with antibiotics to severe, recurring infections to deadly diseases.

Sex is based on intimate contact between delicate tissues, and that allows pathogens to move directly from the blood or bodily fluids of one individual to another. STDs are—or should be—a constant concern among people with multiple sex partners.

Knowledge and Prevention Are Your Best Defenses

Rates of STDs have shown no clear trend in the United States in recent years. Between 1996 and 2006, figures for syphilis went down, those for chlamydia went up, and the numbers for gonorrhea stabilized. HIV rates peaked in 1993, then declined. Since 2001, however, the rate for HIV has slowly gone back up, perhaps due to fading memories of the severity of the disease or an overabundant faith in the drugs that treat HIV. (Although effective, the drugs are expensive, do not cure the disease, and often cause serious side effects.) One-third of all new cases of STD each year are attributable to human papillomavirus, which accounts for the current increases in STD rates. See **Figure 18.24**.

The most effective way to prevent STDs is to abstain from sexual penetration of body orifices. However, those who prefer to be sexually active can use a number of other techniques:

- Having sex only with people who have tested negative for STDs.
- Remaining in a mutually monogamous relationship with a person who started the relationship free of STDs.
- Using barrier techniques, primarily condoms, that prevent pathogen transmission when used properly.
- For sexually active people with multiple partners, getting vaccinated. (Vaccines are only available against certain STDs.)

From a public health standpoint, STDs require a combination of prevention and treatment. For curable diseases, including many bacterial infections, treatment of sexually active patients can prevent them from spreading diseases. In this sense, treatment translates into prevention. For decades, public health officials have engaged in "partner tracing"—tracking down and testing sex partners of people with STDs, especially syphilis and gonorrhea, and then treating if needed. In all states, medical personnel are required to report cases of syphilis, gonorrhea, chlamydia, and AIDS, so that public health agencies can trace partners.

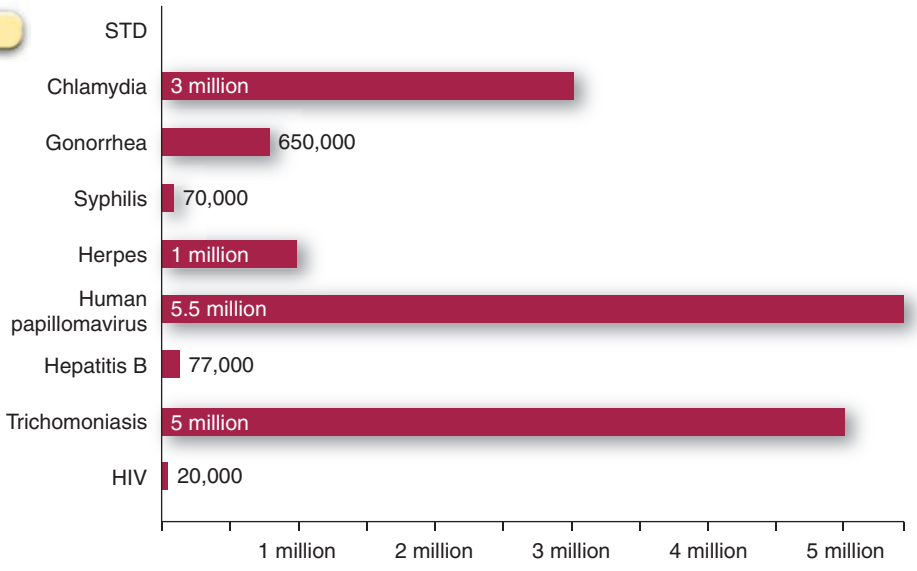
Even during an epidemic, diseases are often considered a personal matter. However, when treatment is imperfect or unavailable (as it is in AIDS, HSV, and avian influenza, for example), prevention becomes the first line of defense. For the good of the community, personal actions become a public affair.

STDs Have Many Causes

STDs may be caused by bacteria, viruses, fungi, insects, or protists. Bacterial STDs include **gonorrhea**, **syphilis**, and **chlamydia**. Viruses that can be transmitted through

Estimated new cases of STDs per year in the United States (2008) • Figure 18.24

WILEY PLUS Video



Sexually transmitted diseases Table 18.2

Common Name	Scientific Name	Classification	Symptoms	Treatment
Chlamydia	*Chlamydia trachomatis*	Bacterial (can only reproduce inside body cells)	Usually asymptomatic, may cause urethritis in males; leads to pelvic inflammatory disease in females	Antibiotics
Gonorrhea or "the clap"	*Neisseria gonorrhoeae*	Bacterial	Urethritis with excess pus discharge; may be asymptomatic in females, leading to sterility	Antibiotics
Syphilis	*Treponema pallidum*	Bacterial (spiral bacterium)	Primary stage results in a painless open sore or chancre; secondary stage is a rash, fever, and joint pain; tertiary stage results when organs begin to degenerate	Antibiotics in primary or secondary stage
Genital herpes	Type II herpes simplex virus (HSV)	Virus	Painful blisters on the external genitals of males and females, with possible internal blistering in females	Incurable, but outbreaks can be controlled with anti-inflammatory drugs
Genital Warts	Human papillomavirus (HPV)	Virus	Cauliflower growths on the external genital area and internal growths in females; can also appear on or around the anus	Incurable; warts can be removed cryogenically
Trichomoniasis	*Trichomonas vaginalis*	Protozoan	Foul-smelling discharge and itching in females	Prescription drug metronidazole

sex include **HIV**, **herpes simplex virus (HSV) 1 and 2**, **human papillomavirus (HPV)**, and **hepatitis B**. HSV 1 causes cold sores in the mouth and, less frequently, genital lesions. HSV 2 causes most cases of genital herpes. Human papillomavirus, or HPV, is a group of viruses that may be sexually transmitted. These viruses cause genital warts and in some cases can lead to cancer of the cervix, anus, penis, or vulva. Currently, the CDC estimates that over 20 million people are infected with HPV. This means that at least 50% of those sexually active get HPV at some point. An amazing 80% of women have contracted HPV by age 50. Because of the prevalence and seriousness of this virus, scientists have been working on a vaccine for a few years. The great news is that a promising vaccine against the most common strain, HPV-16, has been created and was recently deemed safe and effective by the U.S. Food and Drug Administration. Preliminary results are promising, with 100% protection against the most virulent forms of HPV.

Yeast infections are caused by a fungus. Pubic **lice** are insects that burrow into the skin, and **vaginitis** is usually caused by a parasitic protozoan. See Table 18.2 for a list of sexually transmitted diseases.

CONCEPT CHECK

1. **What** are the main categories of STDs?
2. **What** is the treatment for chlamydia, gonorrhea, and syphills? For genital herpes? For genital warts? For trichomoniasis?
3. **How** can STDs be avoided?

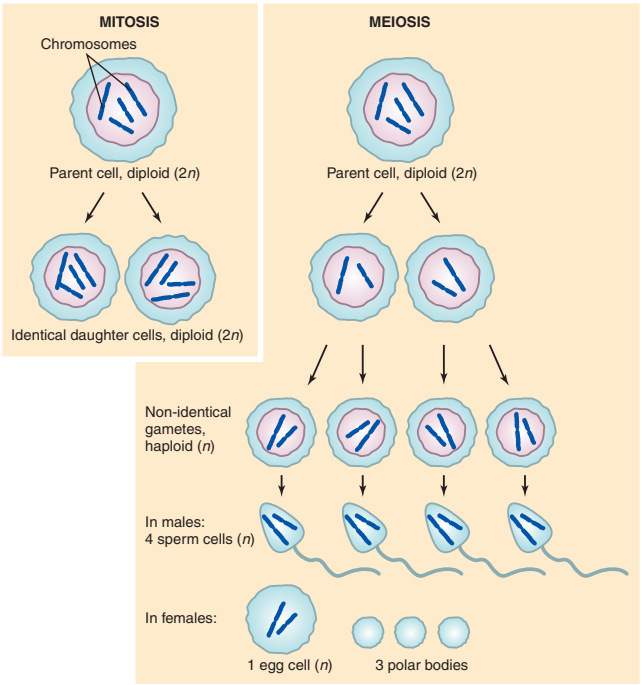
Summary

THE PLANNER

1 Survival of the Species Depends on Gamete Formation 486

- Reproduction is among the most basic human urges, because it is essential to the survival of the species. The reproductive system produces **gametes**, provides a suitable place for the union of egg and sperm, nourishes the developing fetus, and produces the sexual characteristics associated with being male or female.
- As seen here, gametes are produced via meiosis, resulting in haploid cells. Males produce four sperm from each primary spermatocyte, whereas females produce one egg and three polar bodies.

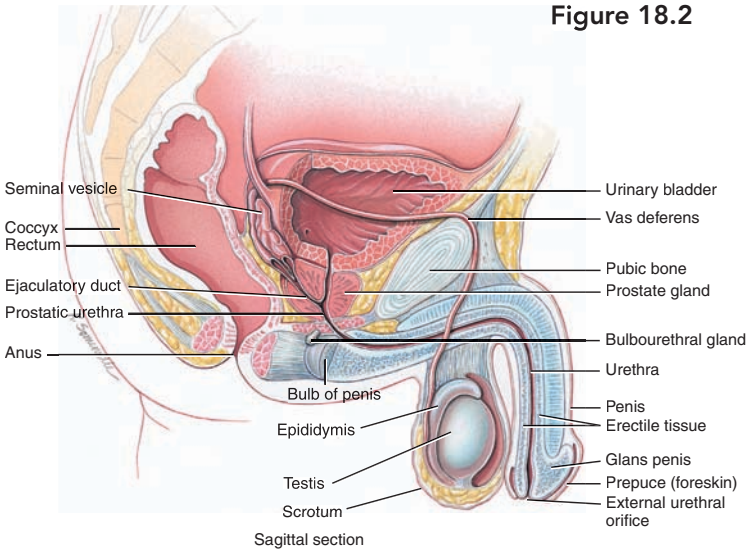
Figure 18.1



2 The Male Reproductive System Produces, Stores, and Delivers Sperm 488

- As shown in this diagram, the male system begins with the testes, the organs that produce sperm. The sperm travel down the epididymis and through a canal into the vas deferens.
- The seminal vesicles add fluid, and then the sperm and developing semen travel through the prostate at the base of the urinary bladder.
- The semen leaves the male via the penile urethra. Glands lubricate the tip of the penis.
- Hormones control the activity of the male reproductive system. FSH and LH are released from the anterior pituitary. FSH stimulates sperm production, whereas LH stimulates the interstitial cells, which produce testosterone, the hormone that creates male secondary sex characteristics.
- The male orgasm, directed by the sympathetic nervous system, causes the release of sperm from the male body. Human sexual response has four phases: arousal, plateau, orgasm, and resolution. Although the specifics are different in men and women, many similar physiological changes occur in both genders.

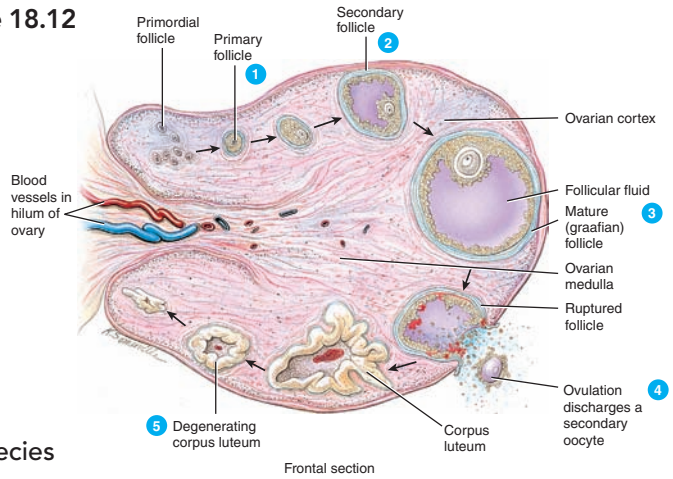
Figure 18.2



3 The Female Reproductive System Produces and Nourishes Eggs 498

- The female reproductive system is composed of the ovaries (pictured here), the uterine tubes, the uterus and the vagina, and accessory organs, including the mammary glands. The ovaries produce eggs, estrogen, and progesterone.
- Estrogen creates the secondary sexual characteristics. The uterus houses the developing fetus, and the endometrial lining is shed once a month during the menstrual

Figure 18.12



flow. Like the male reproductive system, the female reproductive system is controlled by hormones. The anterior pituitary secretes FSH, which stimulates the development of eggs. Developing eggs release estrogen, causing the lining of the uterus to build up. When estrogen levels get high, FSH is inhibited and LH is secreted by the anterior pituitary. LH causes ovulation, and the cells that surrounded the developing egg begin secreting progesterone, which causes the uterine lining to begin functioning, and secreting nutritive fluids. If there is no fertilization, the ovary stops producing progesterone, the blood levels of all female hormones decline, and the uterine membrane is shed.

- Women, but not men, are able to have multiple orgasms.

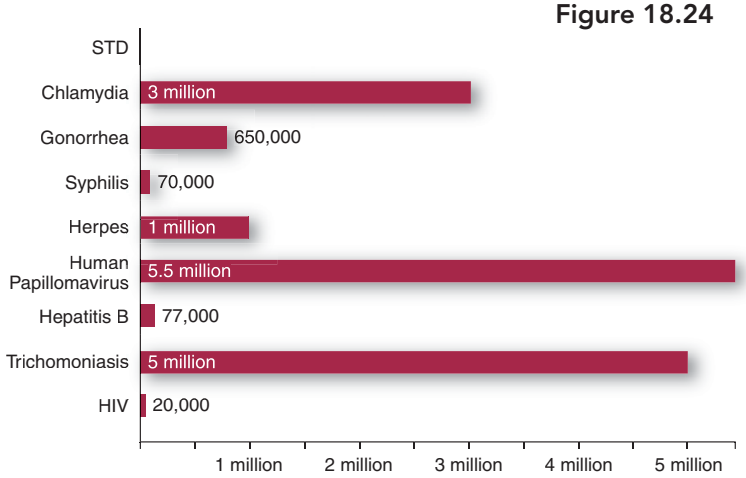
4 There Are Many Birth Control Choices 508

- Birth control is the prevention of conception or implantation.
- The types of birth control include abstinence, surgical procedures, hormonal controls, barrier methods, chemical methods, such as spermicidal creams and jellies, and natural family planning.

5 Sexual Contact Carries a Danger: Sexually Transmitted Diseases 515

- Human sexuality involves close physical contact, and that becomes an effective route for infection by pathogens, including bacteria, viruses, and parasites, some of which are included on this graph.

Figure 18.24



- To protect yourself, know your partner, avoid unprotected sex, and think carefully about your sexual practices. Sex is intimate, both physically and emotionally.

Key Terms

- alleles 486
- atresia 499
- cervix 501
- cGMP 494
- diploid 487
- elective abortion 510
- gametes 486
- haploid 487
- homologous 487
- implantation 501
- lactiferous 503
- laparoscopy 509
- ligating 509
- oocyte 492
- phenotype 486
- prolapse 502
- quiescent 492
- spermatic cord 493
- spermatogenesis 489
- stem cells 491
- urogenital 493

Critical and Creative Thinking Questions

1. FSH is secreted by the anterior pituitary in both males and females. What is the function of this hormone in males? How does that compare to its function in females? What are the similarities in the functioning of FSH in the two genders?
2. The male and female reproductive systems have many analogous structures. List the function of each of the male organs given below, then identify a female organ with similar function. Explain where the female organ is found, and describe the similarities between the two organs.
   testes vas deferens penis
3. Birth control pills maintain a high blood level of estrogen and progesterone. What is happening in the ovary when the blood level of estrogen is high? How is the uterus responding? How does this prevent pregnancy?
4. **CLINICAL CLICK QUESTION**
   Thinking that her menstrual flow was going to be heavy, Tabitha purchased and used "super duty" tampons. She was pleased that her flow was not as heavy as she anticipated, and therefore did not require but a few of these more absorbent tampons. As a matter of fact, she hardly needed to change them and found one was sufficient for two days.

Not three days after her period, however, Tabitha began to feel ill. She had a severe headache, low fever, muscle aches, and chills. She attributed this to a mild cold and did nothing other than try to get some rest. By day four, however, Tabitha had a fever of 103, a sunburn-like rash, a sore throat, severe diarrhea, dangerously low blood pressure causing dizziness and confusion, abdominal pain, and a strangely bright pink tongue. Alarmed, she went to her physician, who immediately put her on IV antibiotics and warned her that she may have other organ involvement before they are able to control this infection.

Where did Tabitha's infection most likely originate? How did Tabitha's actions during her period affect the growth of this bacterium?

Her doctor is concerned that Tabitha may have kidney failure or liver functioning troubles. Look at Figure 18.10 to determine how this bacterial infection may have traveled into Tabitha's abdominal cavity. Describe the route by which this bacterium may have entered Tabitha's body.

Tabitha's doctor admitted Tabitha to the hospital while she recovers from this illness. Why is she admitted? What can the medical staff do to assist in relieving her symptoms listed above?

5. List five types of birth control. Explain how each method prevents pregnancy, and discuss its effectiveness. What is the most reliable method of birth control? What is the least reliable method? Which of these methods also prevent the spread of sexually transmitted diseases?

What is happening in this picture?

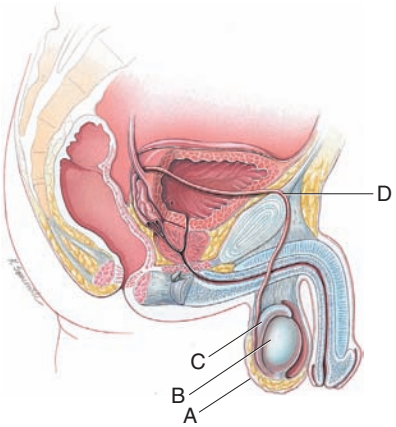
Female trouble. These two words often strike fear into the hearts of men, as it means the woman in their life is suffering from mysterious pain and emotional upheaval that seems to make no sense. These pains and mood swings may occur predictably every month or sporadically over the course of a lifetime. It can be difficult for others to understand what is causing the discomfort the woman is experiencing.

Think Critically

1. During which portion of the female cycle is a woman most likely to experience abdominal cramps? What is the probable cause of these often painfully strong contractions?
2. What hormones are elevated during this time, causing water gain in the tissues, appetite alteration, and overall moodiness of the female?
3. Many over-the-counter drugs are marketed as remedies for menstrual cramps and temporary water-weight gain. How might these remedies affect the body? Can you think of any homeopathic remedies or behaviors that might alleviate uterine cramps?

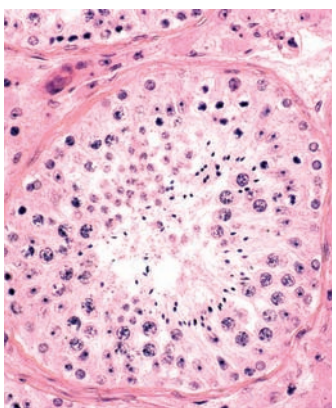
Self-Test

1. The function of the structure labeled A in the figure below is _____.
   a. sperm production
   b. sperm maturation
   c. temperature regulation of sperm
   d. sperm transport



2. Using the same figure, the epididymis is labeled _____.
   a. A
   b. B
   c. C
   d. D

3. The function of the structure shown in the figure below is _____.
   a. spermatid production
   b. testosterone production
   c. inhibin production
   d. both spermatid and testerone production



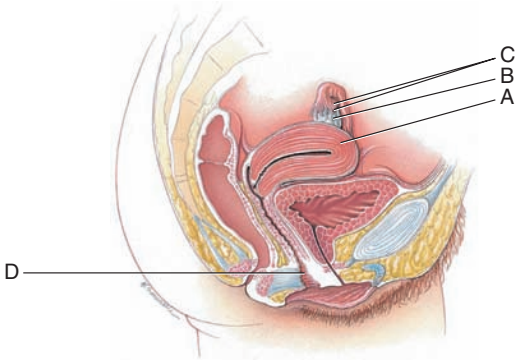
4. The function of the Sertoli cells is to _____.
   a. produce testosterone
   b. protect developing spermatids
   c. promote development of secondary male sex characteristics
   d. undergo meiosis to produce sperm

5. The correct sequence of glands that add fluid to semen during an ejaculation is _____.
   a. bulbourethral gland → seminal vesicles → prostate gland
   b. prostate gland → bulbourethral gland → seminal vesicles
   c. seminal vesicles → bulbourethral gland → prostate gland
   d. seminal vesicles → prostate gland → bulbourethral gland

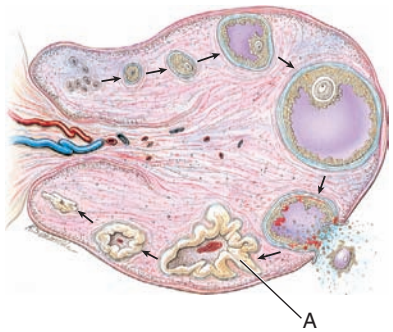
6. The gland in the male reproductive system that contributes most of the fluid of the semen and buffers the potentially lethal acidic environment of the vagina is the _____.
   a. seminal vesicles
   b. prostate gland
   c. bulbourethral glands
   d. corpora spongiosum

7. The function of FSH in the male is to _____.
   a. stimulate production of testosterone
   b. stimulate production of sperm
   c. inhibit release of testosterone from the testes
   d. FSH has no function in the male, only in the female.

8. In the figure below, the organ responsible for producing estrogen is labeled _____.
   a. A
   b. B
   c. C
   d. D



9. The function of the structure labeled A in the figure below is to _____.
   a. produce estrogen
   b. produce testosterone
   c. stimulate secretion of the uterine lining
   d. prevent ovulation



10. In the female, LH is directly responsible for _____.
   a. ovulation
   b. maturation of follicles
   c. buildup of the uterine lining
   d. menstruation

11. The layer of the uterus that repeatedly thickens and sheds under hormonal control is the _____.
   a. endometrium
   b. perimetrium
   c. myometrium

12. The hormone responsible for proliferation of the uterine lining comes from _____.
   a. the hypothalamus
   b. the anterior pituitary gland
   c. secondary and mature follicles
   d. the corpus luteum

13. The birth control method that is also effective against STDs is _____.
   a. spermicidal creams and jellies
   b. the diaphragm
   c. the condom (either male or female)
   d. a vasectomy or tubal ligation

14. The most effective method of birth control, other than abstinence, is _____.
   a. hormonal methods, such as the pill or Depo-provera injections
   b. surgical methods including vasectomy and tubal ligation
   c. natural family planning using temperature charts and observation of cervical mucus
   d. barrier methods combined with spermicidal creams and jellies

15. All of the following STDs can be effectively treated with antibiotics except _____.
   a. gonorrhea
   b. genital warts
   c. syphilis
   d. chlamydia

THE PLANNER

Review your Chapter Planner on the chapter opener and check off your completed work.

19 Pregnancy: Development from Conception to Newborn

Before 1978, every baby could be traced back to the introduction of male sperm into a woman's reproductive tract, usually through sex. Then came Louise Brown, a girl born in England through in vitro fertilization, or IVF.

Louise's parents had tried for nine years to conceive. Mrs. Brown was producing eggs, and her husband's sperm looked healthy, but her uterine tubes were blocked. Her doctor proposed to withdraw an egg with laparoscopic surgery, expose it to sperm in a lab dish, and return the embryo to her uterus. The procedure was done, and the embryo developed into Louise Brown, the world's first "test-tube baby."

IVF rested on a background of animal research: In 1891, rabbit embryos transferred to another animal developed normally. In the 1960s, human eggs were first fertilized in the laboratory. Then in 1978, along came Louise Brown, the first of perhaps 1 million IVF babies. As IVF has become routine, improvements have emerged from our ever better understanding of human reproduction and development. We now understand much more of the dance of chemical messengers directing the development from a fertilized egg into a human being.

Pregnancy and birth create a bond among women worldwide. Females carry the responsibilities of pregnancy, giving of their own body in order to provide nutrition and protection for a new life. What changes occur to allow an embryo and fetus to develop within the mother's uterus? What regulates the timing of each stage of development?

CHAPTER OUTLINE

Days 1 Through 14 Include Fertilization and Implantation 524

- Fertilization Creates an Entire Diploid Genome
- The Growing Human Undergoes Three Kinds of Cell Development
- The Fertilized Egg Becomes a Blastocyst
- The Early Embryo Gets Implanted in the Uterus

The Embryonic Stage Is Marked by Differentiation and Morphogenesis 531

- Medical Technology Can Assist in Conceiving an Embryo
- Embryonic Development Takes Roughly Six Weeks
- The Extraembryonic Membranes Develop into Essential Carriers of Nutrients
- The Placenta Is Essential but Disposable
- The Embryo Becomes Increasingly Human

Fetal Development Is a Stage of Rapid Organ Growth 537

- Fetal Circulation Is Unique
- Fetal Development Occupies the Second and Third Trimesters
- Prenatal Analysis Helps Parents and Medical Professionals

Labor Initiates the End of Pregnancy 543

- Labor Begins with Hormonal Triggers
- Delivery Has Three Stages
- Fetal Development Can Have Many Complications
- The Mammary Gland Provides Milk When Needed

CHAPTER PLANNER

- ❑ Study the picture and read the opening story.
- ❑ Scan the Learning Objectives in each section:
  p. 524 ❑ p. 531 ❑ p. 537 ❑ p. 543 ❑
- ❑ Read the text and study all figures and visuals. Answer any questions.

Analyze key features

- ❑ Biological InSight, p. 524
- ❑ Process Diagram, p. 529
- ❑ I Wonder..., p. 530
- ❑ Health, Wellness, and Disease, p. 534
- ❑ What a Scientist Sees, p. 545
- ❑ Ethics and Issues, p. 547
- ❑ Stop: Answer the Concept Checks before you go on:
  p. 530 ❑ p. 536 ❑ p. 542 ❑ p. 548 ❑

End of chapter

- ❑ Review the Summary and Key Terms.
- ❑ Answer the Critical and Creative Thinking Questions.
- ❑ Answer What is happening in this picture?
- ❑ Answer the Self-Test Questions.

19.1 Days 1 Through 14 Include Fertilization and Implantation

LEARNING OBJECTIVES

1. **Explain** briefly the events of fertilization and implantation.
2. **Compare** a zygote, a morula, and a blastocyst.
3. **Describe** the changes that occur in the zygote.
4. **Explain** implantation briefly.

Maintaining a healthy pregnancy and delivering a child able to survive and grow takes an amazing amount of energy and good timing. The well-orchestrated events of prenatal (meaning "before birth") development can be sorted into three distinct phases:

- The **early embryonic** phase. The ovulated ovum is fertilized by sperm, and the resulting zygote is quickly transformed by cell divisions into a blastocyte that is implanted into the uterus. This phase lasts roughly two weeks and ends with the formation of an embryo.
- The **embryonic** phase. During weeks 3 through 8 an embryo develops and undergoes even more kinds of cell divisions, and after two months it becomes a fetus.
- The **fetal** phase. From weeks 9 through birth, the fetus undergoes yet more spectacular transformations and becomes fully human.

early embryonic Pertaining to the period from fertilization to implantation in the first two weeks; also known as pre-embryonic.

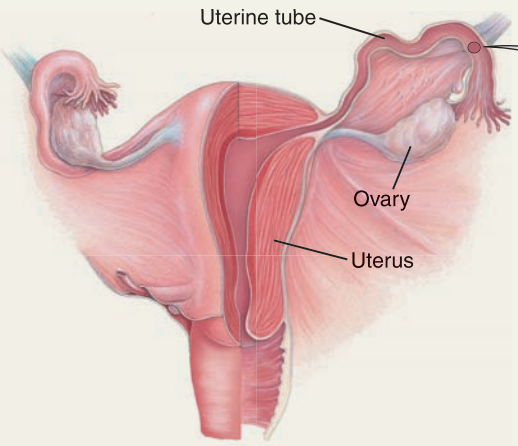
embryonic Pertaining to the period from the end of the second week through the eighth week of development.

fetal Pertaining to the period from beginning of week 9 through birth.

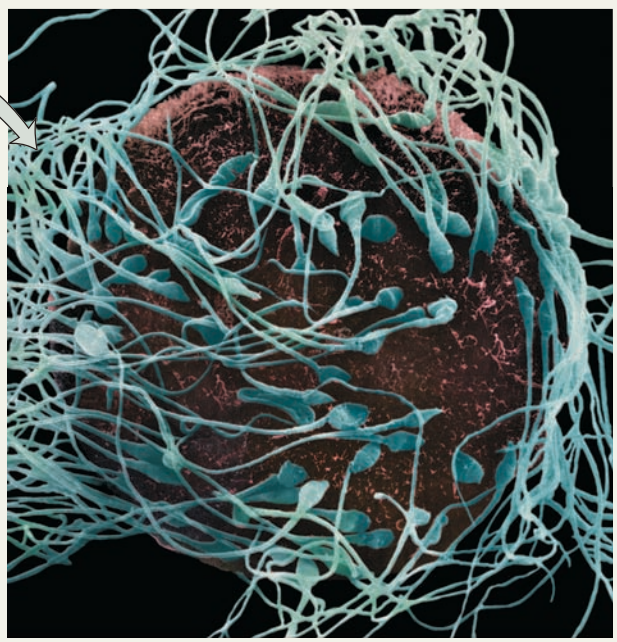
Inside the embryo and later the fetus, development needs precise control, as one cell divides over and over again to form the billions of different cells in the body of the infant. The timing of those divisions, and the completion of major events—such as the development of a heart, a central nervous system, and limbs—are all tightly controlled.

Biological InSight

Fertilization • **Figure 19.1**



Usual position of egg at time of fertilization



Egg surrounded by sperm prior to fertilization

Fertilization Creates an Entire Diploid Genome

Eggs are released inside the female when a spike of luteinizing hormone (LH) triggers ovulation of the most advanced ovarian follicle. After ovulation, the ovum drifts in the female abdominal cavity. LH also causes the fimbriae of the uterine tubes to swell with blood and to sway, creating fluid currents in the abdominal cavity. The waving fimbriae sweep both fluid and the ovum into the uterine tubes, where the ovum may come in contact with sperm introduced into the female tract hours or even days earlier.

After ejaculation, semen does not remain liquid in the female tract, but rather it thickens in the acidic environment of the vagina. The thickening causes the sperm to group together, possibly helping to protect those on the inside of the group from the inhospitable chemical environment of the female tract. This thickening dissolves after a few minutes, and the sperm travel en masse up the vagina, into the uterus and up the uterine tubes. It is important to note that sperm do not demonstrate a will—they do not "search for" the egg—they just whip their tails and move against the slight downward current created by the swaying fimbriae and ciliated cells lining the uterine tubes. This movement carries sperm from the vagina into the cervical canal. From there, the muscular contractions of the female tract and the continued whipping of the sperm flagella propel the sperm forward.

A traveling sperm undergoes **capacitation**—changes that make it able to fertilize the egg:

- The flagellum moves faster.
- The membrane of the sperm head changes so that it can fuse with an ovum.
- The acrosomal enzymes are primed to digest the protective layers surrounding the egg, allowing the male DNA to enter the egg.

The process of capacitation takes approximately seven hours. Any sperm that reaches the ovum before completing capacitation cannot fertilize the egg. However, the sperm gets help: Secretions in the female reproductive tract facilitate fertilization by degrading the sperm's outer surface, removing proteins and other membrane compounds from the head of the sperm.

The ovulated egg is surrounded by the **corona radiata** and the **zona pellucida**, as seen in Figure 19.1. The corona radiata (literally, circular crown) is composed

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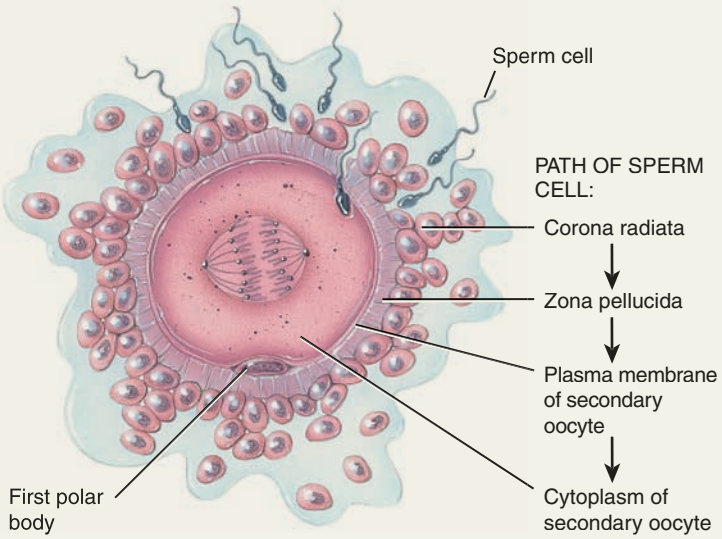
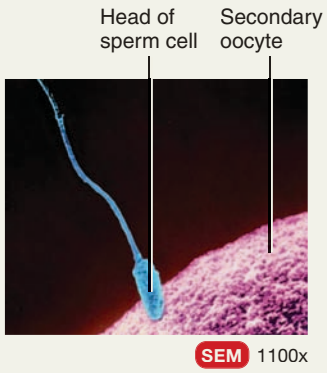
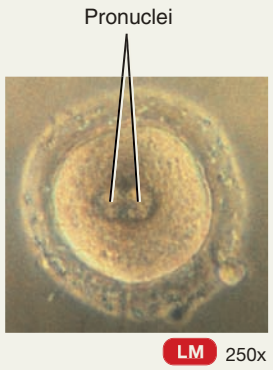


Sperm cell penetrating a secondary oocyte. Only one sperm cell is able to enter the oocyte membrane. This ensures a single sperm will fertilize the egg.



Sperm cell in contact with a secondary oocyte



Male and female pronuclei immediately before they fuse. Once fusion has occurred, a zygote is formed and fertilization is complete.

of cells from the ovarian follicle, still clinging to the ovum. The zona pellucida is a clear-looking layer (*pellucida* means "allowing light through") between the corona radiata and the ovum membrane. The zona pellucida has species-specific receptors for the sperm, explaining why only human sperm can fertilize human eggs. When a sperm binds to its receptor in the zona pellucida, the acrosome activates, releasing its load of digestive enzymes. These enzymes eat away the zona pellucida in front of the sperm while the flagellum continues pushing it forward.

Only one sperm makes its way into the ooctye. One sperm works its way through the zona pellucida and fuses with the oocyte membrane during the process of **syngamy**. It's not entirely clear why only one sperm can enter the oocyte cytoplasm, when many sperm are bound to the zona pellucida receptors and beginning to digest their way through it. At any rate, within seconds after syngamy, the oocyte membrane depolarizes, blocking the entry of all other sperm. This reaction is a block to **polyspermy**, preventing further interaction between the now-fertilized egg and other sperm.

polyspermy Many sperm entering one ovum.

After syngamy, the oocyte finally completes meiosis, creating a mature ovum and a small polar body of "excess" DNA that will degenerate outside the ovum. The male DNA converges into a **male pronucleus** upon entering the ovum, and the mature ovum DNA simultaneously forms a **female pronucleus**. Figure 19.1 shows this process. These two pronuclei will fuse, creating the diploid chromosome complement of the new life. At this point, fertilization is complete. All of the genetic instructions for the new individual are in place. Once they are activated in the proper order, life can begin.

This entire process usually happens in the upper third of the uterine tubes. The ovum is only **viable** for 24 to 48 hours after ovulation. At the normal traveling speed of the ovum, it barely reaches the halfway point of the uterine tubes in 48 hours. Sperm introduced to the female tract can survive for upward of five days, so it may already be present in the upper reaches of the uterine tubes. Fertilization occurs where the living ovum contacts the sperm.

viable Capable of living.

The Growing Human Undergoes Three Kinds of Cell Development

The fertilized egg, called a **zygote**, now begins cell division. Throughout the pregnancy, the developing infant will undergo three basic kinds of cellular division and development:

- **Cleavage**. The zygote undergoes cleavage—a series of rapid cell divisions in the first four days after fertilization. This process does not increase the size of the zygote, but rather it divides the zygote into many cells, forming a ball of cells of roughly the same size as the original undivided zygote.
- **Differentiation**. The cells of the developing infant begin to specialize—to take on different forms and functions.
- **Morphogenesis**. The sum total of all the cell differentiation is morphogenesis—the spectacular changes in shape and functions of the early embryo, embryo, and fetus and their organs and tissues.

cleavage Repeated cell divisions with little time between rounds to enlarge the resulting daughter cells.

differentiation Cellular process that causes a cell to become specialized.

morphogenesis Formation of organs and tissues during development.

Both differentiation and morphogenesis result in growth, since the increasing number of cells causes an increase in size and mass. Cleavage does not result in growth.

As the zygote continues to float down the uterine tubes, carried on small fluid currents created by the cilia of the tubes, it undergoes cleavage. All animals go through the same basic developmental stages at this point, first forming a **morula** (meaning "little mulberry" because of its appearance). The morula is a solid mass of cells, each the same size and each with the capacity to develop into any of the myriad types of cell necessary to form a complete human being.

The **blastocyst** follows the morula stage and is composed of even smaller individual cells. As the cells continue to divide, they push outward, forming a hollow ball. The blastocyst is the stage of development where cells begin to specialize, as you will learn in the next section. It is immediately prior to this point, during the morula stage, that identical (monozygotic) twins can be formed.

Many people consider that a new life begins in the female reproductive tract, as an ovulated ovum is fertilized. However, this new life will not be able to survive on its own for many months, raising considerable controversy. Does the new life start as soon as fertilization occurs, or does it start only after that life can survive outside the mother? This is a question that individuals must answer for themselves.

The Fertilized Egg Becomes a Blastocyst

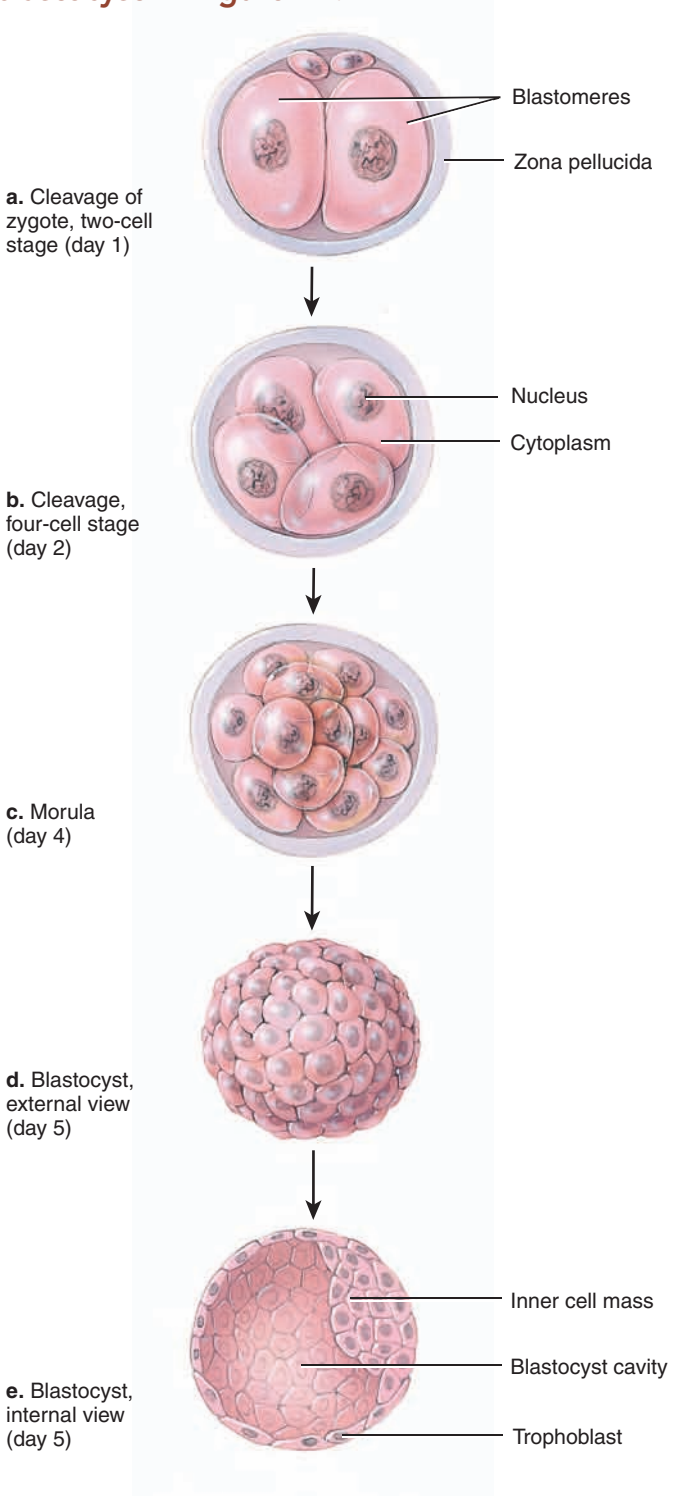
During the blastocyst stage of development, some cells of this hollow ball form an inner cell mass, and others remain as the outer surface, as seen in Figure 19.2. The placement of these cells determines what they will eventually become: embryo or supporting structures. Because most of the cells will form supporting structures rather than components of the actual embryo, this stage of development is sometimes referred to as the pre-embryonic phase.

As the blastocyst forms, the cytoplasmic levels of RNA increase in each of its cells. Recall that RNA level reflects the rate of protein synthesis. Originally, maternal mRNA was abundant in the egg. During fertilization and cleavage, ribosomal RNA increases along with overall translation activity. During the midblastula phase, the translation rate of the maternal mRNA is extremely high, but the sperm's mRNA is largely silent. This means that the proteins being created during blastula formation are mostly maternal in origin. As the embryo passes through the blastula stage, maternal mRNA translation is **down-regulated** (slowed down) in favor of embryonic mRNA transcription and translation. The genes inherited from the mother and the father are expressed equally after this point.

With the blastocyst formed, the cells begin to differentiate. Some will become nutritive layers, forming the **placenta**; others will become protective layers; still others will form the embryo itself. The most remarkable cells in the blastocyst are a group of **pluripotent** cells at the center. Each of these stem cells has the potential to become any adult cell type, and these cells are the focus of current stem cell research.

An outer layer of cells, the **trophoblast**, surrounds the inner cell mass. This layer will contact the endometrial lining around day 7 and begin to release enzymes to digest its way into the endometrium. The trophoblast releases the hormone human chorionic gonadotropin (hCG), which keeps the corpus luteum alive and is useful in detecting pregnancy and is described later in this chapter.

Development of the morula and blastocyst • Figure 19.2



The blastocyst travels the length of the uterine tube and reaches the uterus in about four to five days. For an illustration of the events of the first week of development, see **Figure 19.3**. Once it drops from the uterine tube, the blastocyst floats freely in the uterine cavity for a day or two. The uterus is now in the midst of the secretory phase, with the thick, spongy endometrium producing nutritive fluids.

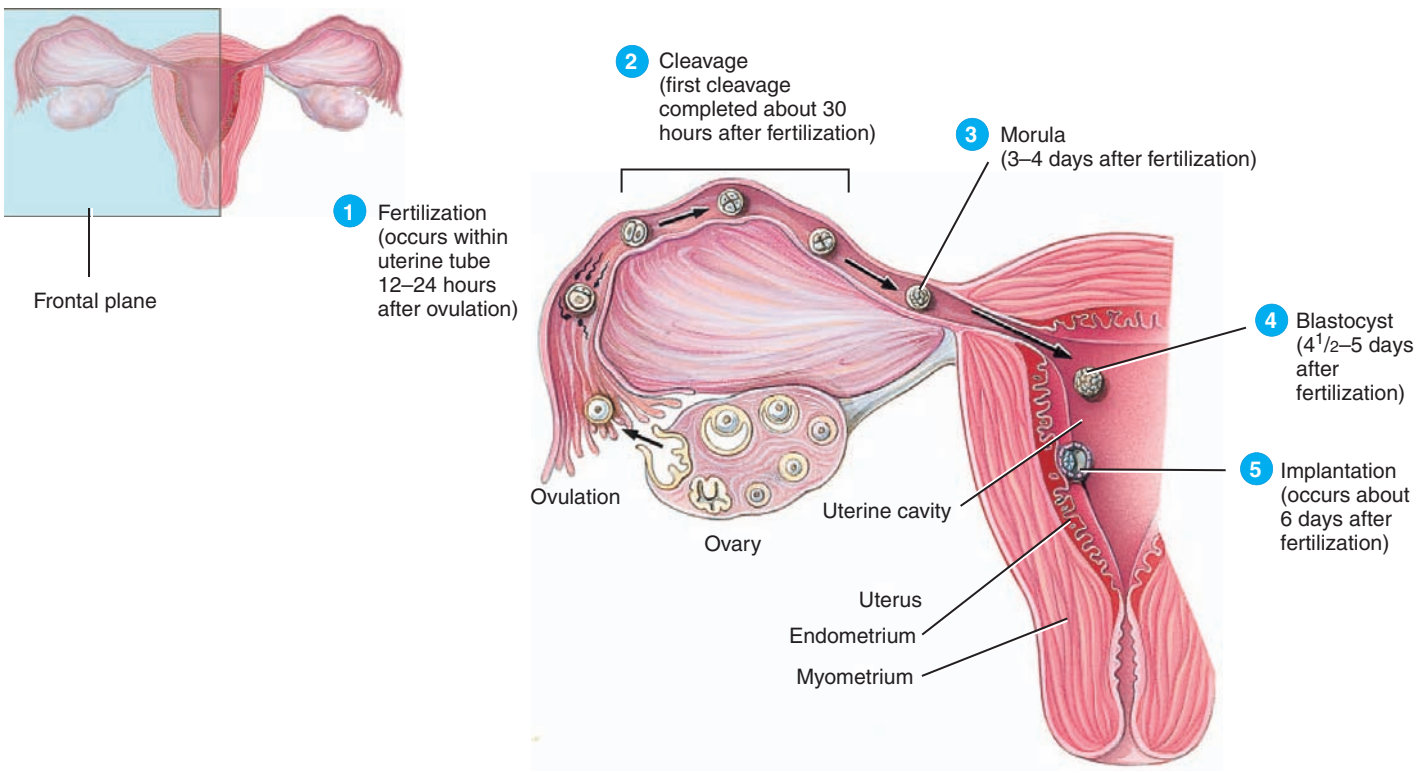
The Early Embryo Gets Implanted in the Uterus

Implantation occurs as the blastocyst tentatively attaches to the uterine wall. A day later, the blastocyst attaches much more firmly to the uterine endometrial wall. The cells of the trophoblast digest the endometrium, burrowing into the spongy tissue and leaving no trace on the surface. Attachment causes endometrial glands near the blastocyst to enlarge and increase secretions. New blood vessels form to deliver more blood to the implanted blastocyst. See **Figure 19.4** for a look at implantation and a summary of the events of the second week after fertilization. It is during this time that twinning may occur. For more on twins, see *I Wonder… What Causes Twins, and How Do They Contribute to the Study of Genetics and Human Development?* on page 530.

As the trophoblast enzymes digest the endometrium, the blastocyst trophoblast develops into the **chorion**. This tissue, one of the fetal membranes, will form the exchange membrane between fetal and maternal blood. As the embryo develops, this layer surrounds the new life. Eventually, the chorion becomes the main embryonic contribution to the placenta.

Blastocyst placement can cause problems. The most troublesome problem that can arise is related to the placement of the blastocyst. The blastocyst settles more or less at random in the uterus, usually in the upper back or the body of the uterus. If it settles lower in the uterus, a life-threatening condition called **placenta previa** ("placenta first") may develop. The placenta grows near or over the cervical opening of the uterus, blocking the passage of the fetus during birth. This condition can cause maternal hemorrhaging before or during labor.

Primary events of the first week of development • Figure 19.3



Frontal section through uterus, uterine tube, and ovary

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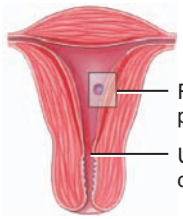
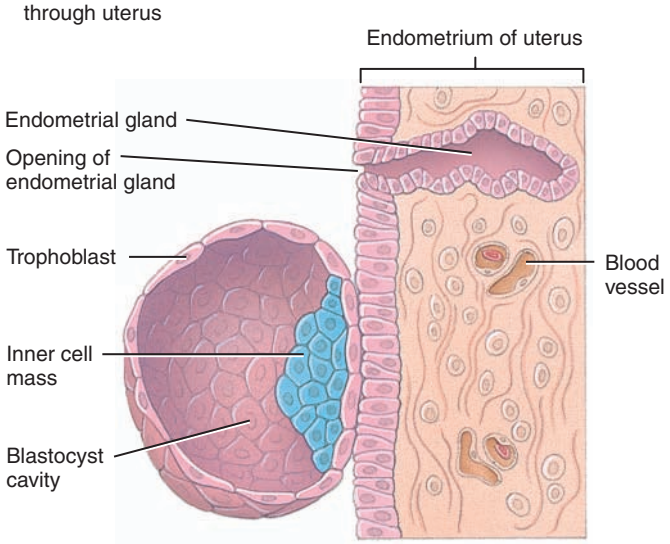
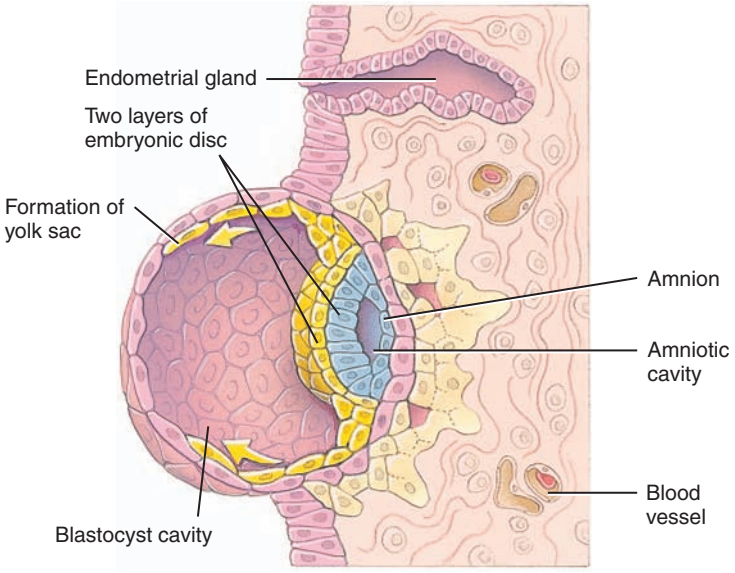
Implantation and the primary events of the second week of development • Figure 19.4



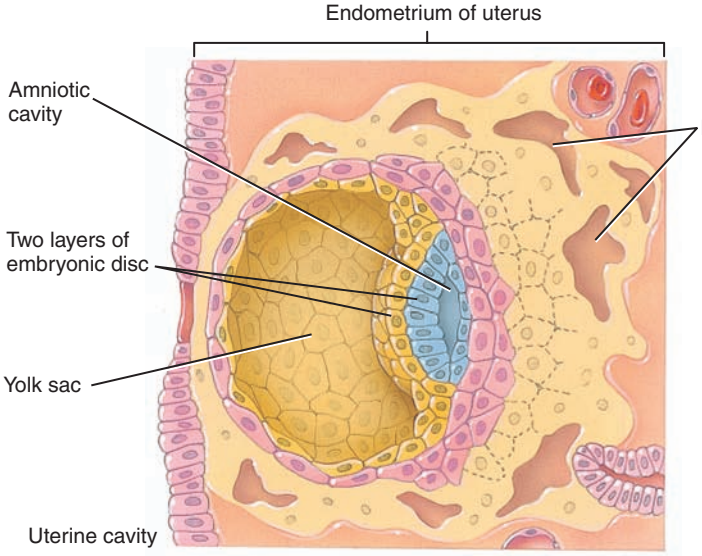
Frontal section through uterus



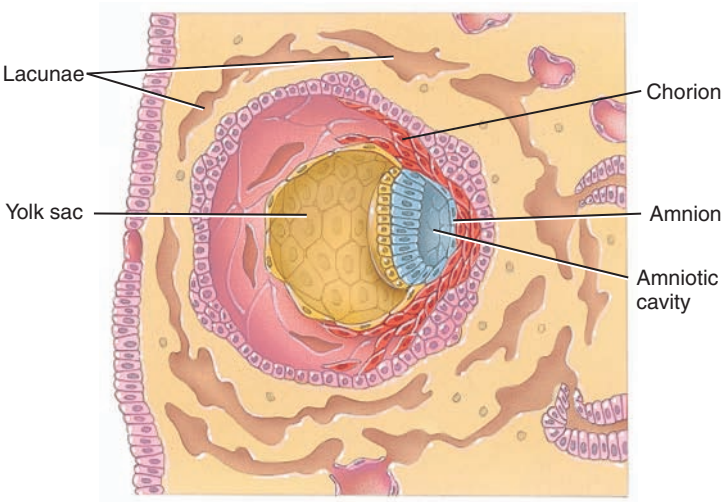
a. Frontal section through endometrium of uterus and blastocyst, about 6 days after fertilization



b. Frontal section through endometrium of uterus showing blastocyst, about 8 days after fertilization



c. Frontal section through endometrium of uterus showing blastocyst, about 9 days after fertilization



d. Frontal section through endometrium of uterus showing blastocyst, about 12 days after fertilization

I WONDER...

THE PLANNER

What Causes Twins, and How Do They Contribute to the Study of Genetics and Human Development?

Two babies at once can be a mixed blessing. Double the joy, double the diapers, double the college costs! Some twins are difficult to tell apart, while others are no closer in appearance than any other pair of siblings.

Twins are either fraternal or identical. Fraternal twins grow from two separate fertilization events. If two eggs are ovulated at once, two viable eggs may be present when sperm is introduced. Both may be fertilized. Two separate eggs and two different sperm form two unique zygotes that are, genetically, merely siblings. The only difference between these siblings and perhaps you and your sister or brother is that these siblings develop in the uterus at the same time.

Identical twins, in contrast, arise when one zygote splits into two separate balls of cells as it rolls toward the uterus. Because these embryos trace their genetic lineage to one fertilization event, both balls of cells carry exactly the same DNA. Both embryos use the same DNA during implantation and growth into a fetus and then a baby. Subtle changes in appearance and personality result from the microenvironment surrounding each implanted embryo in the uterus, as well as subtle alterations in the regulation and timing of gene expression in each baby. Even so, identical twins can be hard to distinguish, sometimes even for those as close to them as their parents!

A second, less troublesome condition concerns the orientation of the uterus, which is usually tipped toward the front, lying over the urinary bladder. Approximately one-quarter of women have a **retroverted** or **tipped uterus**, with the uterus lying against the rectum. A tipped uterus may cause some pain during intercourse or menstruation but seems to have no effect on fertility or pregnancy. During implantation, the tipped position of the uterus does not seem to have any effect on the placement of the embryo. Regardless of its original position, the uterus will expand normally into the pelvic cavity as the pregnancy proceeds.

The blastocyst's inner mass develops. During implantation and development, the blastocyst's inner mass is developing. These cells first divide into two layers, called jointly the **embryonic disc**. Inside this disc, the **amniotic cavity** forms. Another sac-like structure develops in the inner cell mass around day 8 as seen in Figure 19.4. A yolk sac is formed in humans, but it is noticeably low in the nutritive yolk that would be found, for example, in a chicken egg, because humans get their nutrients from the placenta rather than a yolk. Yet the yolk sac remains, providing some nutrition to the embryo during the second and third week. By the fourth week of development, cells from the yolk sac are migrating to the embryo and helping to form the respiratory and digestive systems. After nine weeks, the human yolk sac ceases all biological activities.

amniotic cavity
The fluid-filled cavity that bathes the developing embryo and fetus.

CONCEPT CHECK

STOP

1. **Where** does fertilization usually take place? At **what** stage is the developing embryo when implantation occurs?
2. **How** is a zygote different from a morula? **What** defines a blastocyst?
3. **What** are cleavage, differentiation, and morphogenesis?
4. **What** is the function of the trophoblast?

19.2 The Embryonic Stage Is Marked by Differentiation and Morphogenesis

LEARNING OBJECTIVES

1. **Discuss** the various methods of medically assisted conception.
2. **Outline** the function of the three germ layers in the embryo.
3. **Explore** the physiology of the extraembryonic membranes.
4. **List** the milestones of the embryonic period of development.
5. **Describe** the formation and functioning of the placenta.

By day 14, the blastocyst's inner cell mass begins to split, forming the embryonic disc that we have already mentioned. This disc includes two cell types: the **endoderm** and the **ectoderm**. Once the amniotic cavity and these two cell layers appear, the developing organism has passed into the **embryonic stage**.

endoderm The innermost embryonic cell layer.

ectoderm The outer cell layer in the embryo.

All of the changes to date have occurred within the two weeks before the expected menstrual period. The mother-to-be is often unaware that she has conceived at this point, as her cycle is not yet visibly disrupted. She may not be taking precautions in her diet or changing her activity level to benefit the developing embryo. It is estimated that upward of half of all conceptions do not result in successful implantation and pregnancy due to the myriad hazards of the early embryonic stage, which include congenital defects in the zygote, mistakes in genetic control during the intricate processes of this phase, or even subtle environmental disturbances in the uterus and endometrium caused by ingested toxins or maternal lack of essential vitamins, minerals, or macronutrients.

Medical Technology Can Assist in Conceiving an Embryo

Given how much must go right in order to create a viable embryo, it is a miracle that so many successful pregnancies occur. Some couples, in fact, do find it impossible to get past conception. Perhaps ovulation does not occur properly, so eggs are not released, or the uterine tubes are scarred, obstructing the fertilized egg. Perhaps the male has difficulty introducing sperm properly. Infertility can also arise from hormonal imbalances, anatomical malformations, defective eggs or sperm, or congenital defects of the reproductive system. Modern medical technologies can assist in conception in cases where the anatomy of the two people is intact, but the physiology is not functioning properly.

IVF mixes the egg and sperm in a dish. One fertility procedure is called in vitro fertilization (IVF) or pre-embryo transfer. In IVF, eggs are removed from the maternal ovaries, examined for health, and mixed with sperm from the paternal donor **in vitro**, or in laboratory glassware, as opposed to the usual "in vivo" (in life) fertilization process. Often, the mother is given a two-week course of fertility drugs, including FSH and LH, to ensure the availability of a large number of harvestable mature eggs. After the eggs and sperm are mixed, the physician will maintain the resulting pre-embryos in the laboratory in the correct physiological environment. After two days, the usual time needed for the blastocyst to enter the uterus, the physician places two to four healthy blastocysts in the mother's uterus, where they settle and implant as usual. If all goes well, the early embryos will implant, form a placenta, and at least one will develop normally. Success rates are increasing as technologies advance. The hormones used to stimulate follicle development are more potent, allowing more eggs to be harvested. Maintaining the endometrial lining is now easier with a better hormone mixture, and even the tools for harvesting and growing the embryos are advancing.

This procedure makes many fraternal twins and even triplets, as many embryos are introduced, each with the potential to implant. Twins occur in the general populace approximately once in every 80 births, and triplets are even more rare, occurring on the order of 1 in 10,000. By comparison, the rate of fraternal twinning in successful multiple embryo IVF transplants is 25%, and the rate of triplets is 2–3%. It is quite rare for IVF identical twins to appear, as that requires one IVF embryo to split prior to implantation.

ZIFT implants in the fallopian tube. Zygote intrafallopian transfer (ZIFT) technology also creates conception in a laboratory, but relatively quickly implants the zygotes, which may or may not have undergone rudimentary cell division, into the woman's fallopian tube. The zygotes continue to mature until they reach the uterus, where it is expected they will implant as usual. Identical twinning occurs in this process with the same frequency as in natural fertilization.

GIFT mixes egg and sperm in the fallopian tube. Gamete intrafallopian transfer (GIFT) goes even further, extracting eggs from a woman's ovaries and sperm from a man, then inserting them via catheter before conception into the woman's fallopian tubes. In this case, any conception occurs inside the fallopian tube.

Both ZIFT and GIFT require a surgical procedure and can only be accomplished in a woman with healthy fallopian tubes. About 98% of all assisted conceptions occur via IVF. However, in cases where IVF has failed, sometimes ZIFT or GIFT succeeds, for unknown reasons. GIFT is also an appropriate conception assistance technology for those with a religious objection to conception occurring outside the body.

Embryonic Development Takes Roughly Six Weeks

Embryonic development proceeds from weeks 3 through 8. During this time, the embryo undergoes rapid growth, differentiation, and morphogenesis. An almost incomprehensible array of biochemical changes occurs within these six weeks. Everything must be timed exactly, or disaster can result. The rate of natural miscarriage during this period is thought to be nearly 20%.

mesoderm Middle layer of embryonic cells.

The development of a third cell type—the **mesoderm**—is the first landmark reached by the embryo. The three germ layers—endoderm, ectoderm, and mesoderm—eventually develop into the four tissue types of the body: epithelium, connective tissue, muscular tissue, and nervous tissue. **Figure 19.5** shows the crucial period from week 3 to week 5 and beyond. Ectoderm is on the outer surface of the embryo, in contact with the amniotic fluid. From this layer emerges the epidermis, the entire nervous system, portions of the eyes and teeth, the posterior pituitary gland, and the adrenal medulla. Endoderm, the innermost layer, produces the alveoli, liver, most endocrine glands (pancreas, thyroid, parathyroids, anterior pituitary gland, and thymus), tonsils, portions of the inner ear and the epithelial linings of the digestive tract. The mesoderm develops between the endoderm and the ectoderm. It is responsible for the dermis, all connective tissues including the skeletal system, muscles, blood, kidneys, testes or ovaries, and the reproductive ducts, as well as the lymphatic vessels.

The Extraembryonic Membranes Develop into Essential Carriers of Nutrients

During the embryonic stage, as all this activity is taking place inside the embryonic disc, the **extraembryonic** (meaning "outside the embryo") membranes are also developing. The four extraembryonic membranes are the **amnion**, the **allantois**, the **yolk sac**, and the **chorion**. Each provides vital support to the embryo and fetus.

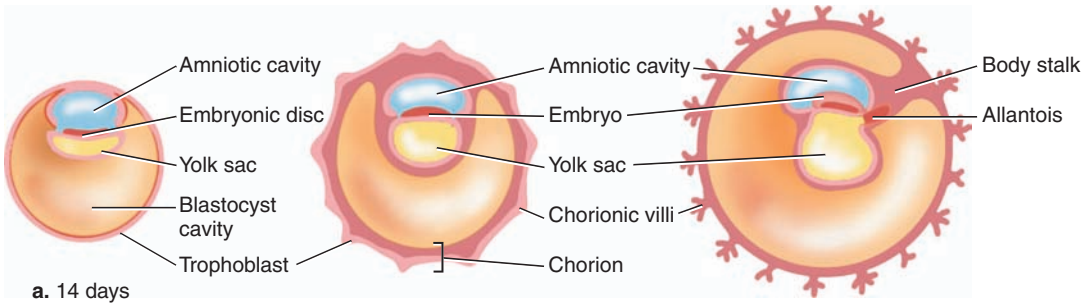
extraembryonic Outside of the cells of an embryo.

The amnion lines the amniotic cavity. The amnion, closest to the embryo, lines the amniotic cavity, providing a diffusion area for the **amniotic fluid**. Amniotic fluid is derived from maternal **interstitial fluid** and is

interstitial fluid Fluid that fills the spaces between cells of tissues.

Embryonic development • Figure 19.5

Weeks 3 through 5 show rapid cellular growth and differentiation into the endoderm, ectoderm, and mesoderm, which will give rise to the four tissue types of the body.



a. 14 days **b.** 18 days **c.** 21 days

cleansed of embryonic and fetal waste products by diffusion across the amniotic membrane.

The amniotic fluid protects the developing embryo and fetus from outside injury, allows free fetal movements so the muscular system can grow symmetrically, maintains a constant temperature, and permits proper lung development. Later, when the fetal kidneys begin to function, urine is formed. The fetus will release urine into the amniotic fluid where it diffuses across to the maternal bloodstream. The compounds of the fetal urine are then removed from the mother's bloodstream by her kidneys. The amniotic fluid also provides a protective cushion for the embryo and fetus. The fluid is noncompressible, so it transmits blows and shocks that could harm the fetus throughout the volume of the amnion. The amniotic fluid is mostly water, and water has a high latent heat—a large amount of energy is needed to change its temperature. Consequently, the embryo's temperature remains stable. The embryo and fetus can move within the amniotic fluid, stretching and pushing against the uterine walls; this activity helps develop muscle mass in the limbs. Finally, embryonic and fetal development cannot occur in a dry environment. The amnion keeps the developing cells of all organs, including the lungs, from drying out.

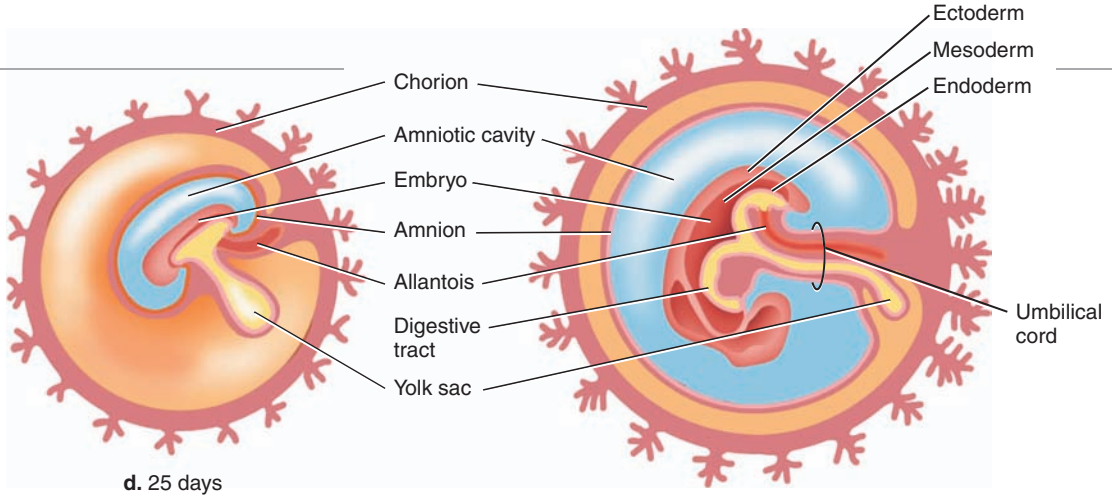
The allantois is the start of the umbilical cord. The allantois provides the starting material for the blood vessels of the **umbilical cord**. These vessels will transport fetal blood to and from the placental exchange surfaces, where oxygen, nutrients, and waste materials are diffused. Once the vessels form, the allantois degenerates.

umbilical cord The flexible cord that connects the fetal circulatory system with the placenta.

The yolk sac will become part of the digestive and respiratory tracts. The yolk sac forms from the endoderm. In some animals, the yolk sac nourishes the developing embryo, but in humans the placenta plays this role. Our yolk sac eventually becomes part of the digestive and respiratory tracts. This membrane also produces fetal blood cells until the bone marrow can take over. The yolk sac may also be involved in gamete production; preliminary research indicates that **germ cells** are first produced there. These germ cells migrate to the gonads, where they differentiate into primary oocytes or spermatogonia.

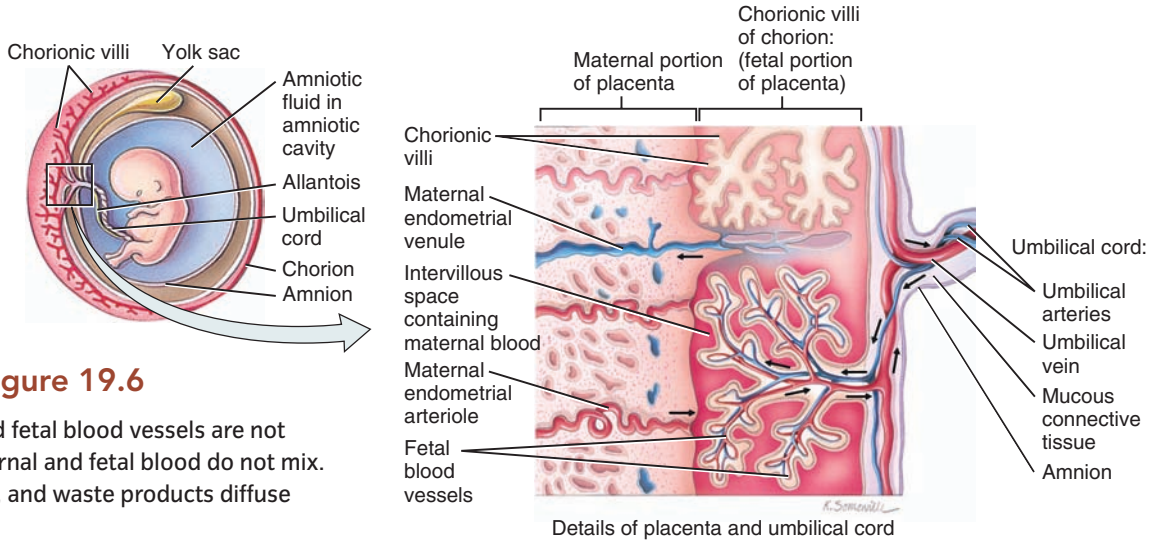
germ cell A cell destined to become an egg or sperm.

The chorion is the source of hCG. The chorion, the outermost layer of the extraembryonic membranes, develops from the trophoblast and makes up the exchange portions of the placenta. It is also responsible for producing **human chorionic gonadotropin (hCG)**, a hormone that maintains pregnancy until the placenta is fully functional, by preventing degeneration of the corpus luteum. With hCG present, the corpus luteum will continue to produce progesterone and other hormones, which maintain the uterine lining rather than permit it to slough off, as usually occurs in the uterine cycle. hCG is the hormone detected in early pregnancy tests. These tests usually show a color change when a particular subunit of the hormone hCG reacts with the test substances. These tests can boast 99% accuracy in identifying pregnancy because if hCG is detected, it must be coming from an implanted embryo whose chorion is producing hormones to maintain the pregnancy. A positive test is an accurate indication of an implantation and a developing chorion. If no hCG is detected, the levels may be too low for the test to recognize. Therefore, a negative test does not guarantee that no developing chorion is present.



d. 25 days

e. 35+ days



Chorionic villi • Figure 19.6

Note that the maternal and fetal blood vessels are not joined to each other. Maternal and fetal blood do not mix. Instead, oxygen, nutrients, and waste products diffuse across cell membranes.

The Placenta Is Essential but Disposable

The placenta is unique: this organ is necessary for embryonic and fetal development but is disposable. The placenta develops as the embryonic **chorionic villi** extend into the endometrium of the uterus, as seen in **Figure 19.6.** The chorion develops finger-like extensions that protrude into the thickened endometrial lining. Together, these two tissues form diffusion surfaces, with only one layer of cells separating fetal blood from maternal blood. Just like their parent material (the trophoblast), the chorionic cells con-

HEALTH, WELLNESS, AND DISEASE

Is Morning Sickness Normal?

THE PLANNER

Pregnancy is often a time of great joy. For a full one-third of all pregnant women, however, the initial stages of pregnancy can be miserable. Morning sickness is a general term used to describe feelings of nausea and vomiting that occur during the first months of pregnancy. Morning sickness usually begins during the first month, and continues through weeks 14 to16. Symptoms include feeling lightheaded or faint upon arising in the morning, tiredness, nausea or vomiting in the morning, nausea when faced with foods or when smelling certain foods, and vomiting without illness. Symptoms are strongest in the morning, but may peak again later in the day. Although the causes of morning sickness remain elusive, most scientists believe it is caused by rapidly rising levels of HCG in the blood during this time. By the end of the third month, blood levels of HCG have decreased along with the symptoms of morning sickness.

Although unpleasant, most cases of morning sickness pass without incident, causing no harm to the developing baby or mother. In some cases, however, weight loss occurs and the health of both the mother and the baby are jeopardized. Extreme nausea and vomiting can persist if the mother is carrying twins, triplets, or more. This may develop into a serious condition, hyperemesis gravidarum, which leads to dehydration and dangerous maternal weight loss. As with less severe morning sickness, this too peaks during weeks 2 to 12 and slowly disappears during the pregnancy.

Treatment for both hyperemesis gravidarum and morning sickness involve reducing the nauseous feelings. Eating crackers before arising in the morning sometimes settles the stomach. Drinking plenty of fluids during that portion of the day when nausea is lessened helps prevent dehydration, and taking a vitamin B6 supplement often helps suppress nauseous feelings. Physicians shy away from prescribing medications for fear of harming the developing embryo. However, if the symptoms are severe enough to present risks to the baby or the mother, she will be admitted to the hospital and given nutritive fluids through an IV.

tain digestive enzymes that eat into the endometrium, damaging it and causing the maternal blood to pool. Chorionic villi, loaded with capillaries, extend into these pools, allowing diffusion across their thin membranes.

All these activities require a fetal heart to pump blood to and from the placenta. By the fifth week, the embryonic heart is strong enough to take advantage of the two umbilical arteries created by the yolk sac.

The placenta works like a large diffusion filter, allowing the exchange of nutrients, gases, and antibodies between mother and the developing infant, but the placenta is not a perfect filter. HIV, alcohol, cocaine, and other damaging substances can cross the placenta. Even prescription drugs, if introduced to the embryo during critical stages, can cause extreme damage.

The placenta also provides hormones. In addition to providing nutrition and oxygen, the placenta also produces a range of hormones responsible for maintaining pregnancy. Early in the pregnancy, the placenta secretes hCG, which in turn stimulates the corpus luteum to remain viable. Progesterone and estrogen from the corpus luteum prevent the loss of the endometrium while implantation occurs. Eventually, the placenta will secrete these hormones on its own in far larger quantities. The main effects of these hormones are to increase the size and strength of the uterine muscle, prevent loss of the endometrium, inhibit uterine contractions during pregnancy, and create a thick mucus plug at the cervix, which helps prevent uterine infections. Sometimes these hormones have unwanted side effects. See *Health, Wellness, and Disease: Is Morning Sickness Normal?*

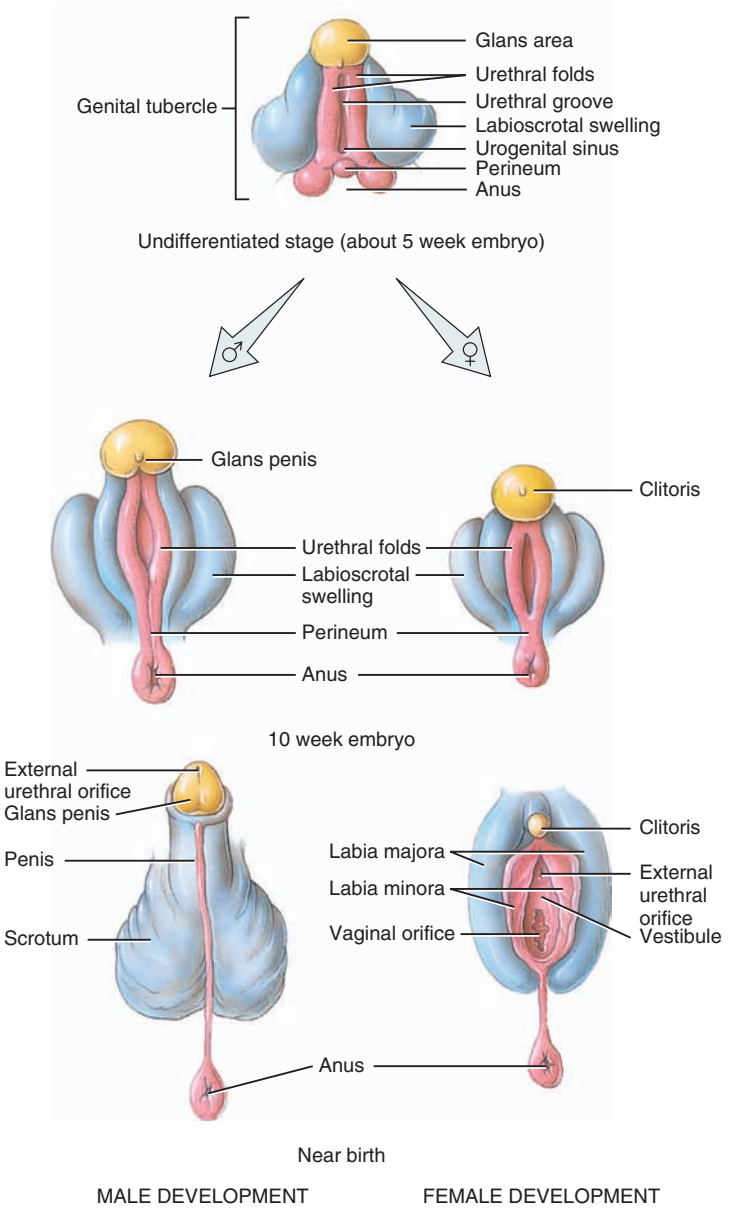
The Embryo Becomes Increasingly Human

From weeks 5 through 8, the embryo becomes increasingly human in appearance. The tail that appeared in the first month regresses, the head enlarges, limb buds that appeared in the first month are forming structures that look very much like arms and legs, hands and feet, and the gonads are formed. The nose is flat, the eyes are widely spaced and open, but the face is obviously human. By week 8, all the major organs and organ systems are present, though not fully functional.

Gender differentiation occurs at approximately seven weeks. Prior to the seventh week, male and female development is exactly the same, with two distinct sets of reproductive tubes and no differentiation between male and female. In the seventh week, if a Y chromosome is present, the male tubes will be stimulated, testes will develop, and release of testosterone from the new testes will cause male sexual characteristics to form. If no Y chromosome is present, the organs destined to become the testes degenerate and the organs primed to develop into the ovaries will mature instead. **Figure 19.7** depicts genital development from week 5 to birth.

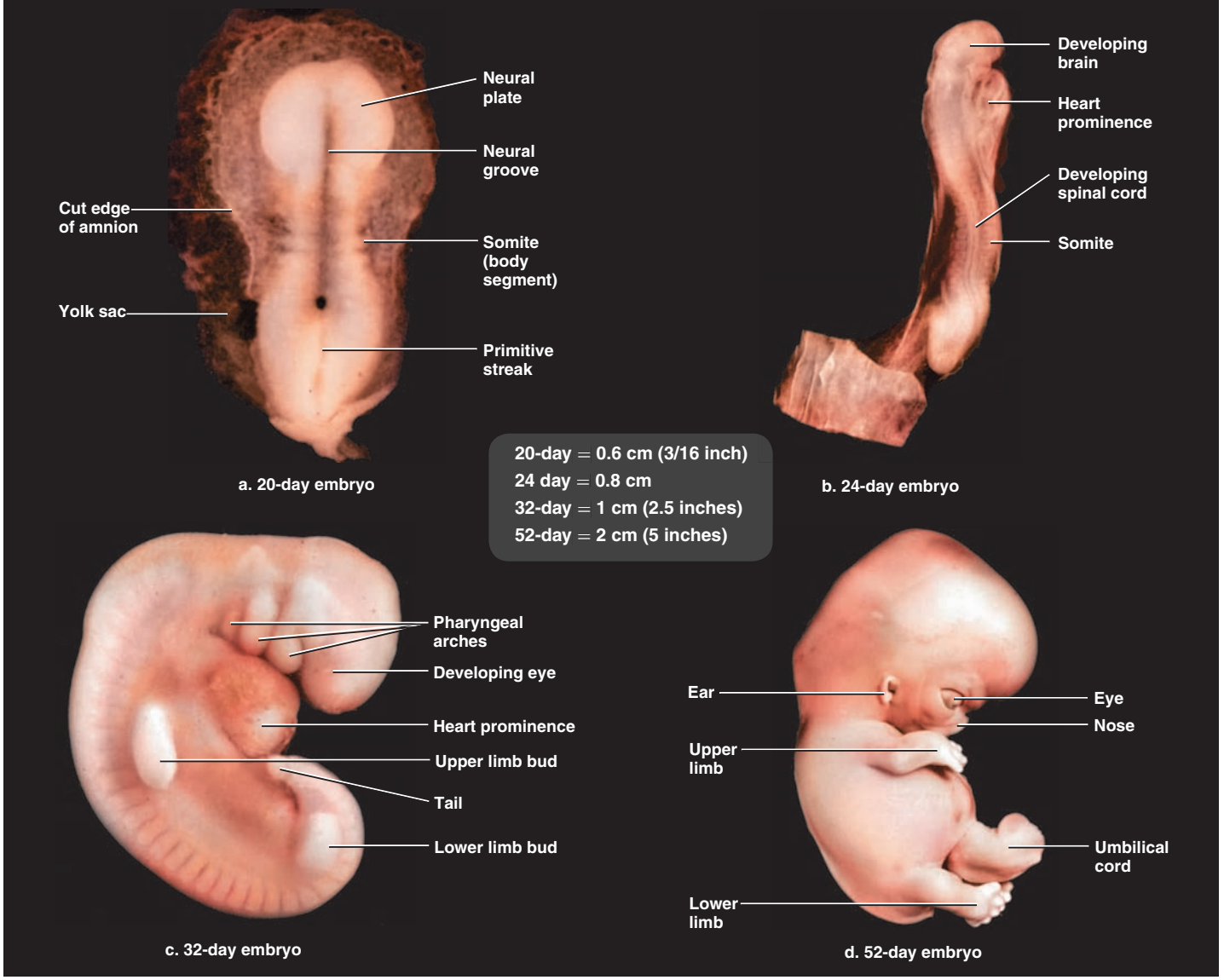
External genital development • Figure 19.7

Genes on the Y chromosome direct the fusion of the urethral folds and the development of the labioscrotal swelling into a scrotum. If there is no Y chromosome present, the urethral folds will not fuse, but instead become the labia minora in the female. The labioscrotal swelling will develop into the labia majora in the absence of a Y chromosome.



Summary of development events of the embryonic period • Figure 19.8

By the end of the eighth week, the embryo's eyes are open, the limbs are visible, digits are distinct, and the tail has disappeared.



By week 8, the embryo is transformed. By the end of the embryonic period, the newly forming individual is approximately 2.5 centimeters (1 inch) long, with a recognizably human form. All the internal and external structures are present at the end of this phase, as shown in **Figure 19.8**. The placenta is mature and functioning.

CONCEPT CHECK

STOP

1. **What** are some methods of medically assisted conception and **how** do they work ?
2. **What** will develop from the endoderm, the ectoderm, and the mesoderm?
3. **What** are the four extra embryonic membranes and **what** are their functions?
4. **What** are the milestones of the embryonic period of development?
5. **What** are the functions of the placenta?

19.3 Fetal Development Is a Stage of Rapid Organ Growth

LEARNING OBJECTIVES

1. **Explain** how fetal circulation differs from neonatal.
2. **Describe** the main events of the second and third trimesters of development.
3. **Differentiate** chorionic villus sampling from amniocentesis.
4. **List** the developmental changes that precede birth.

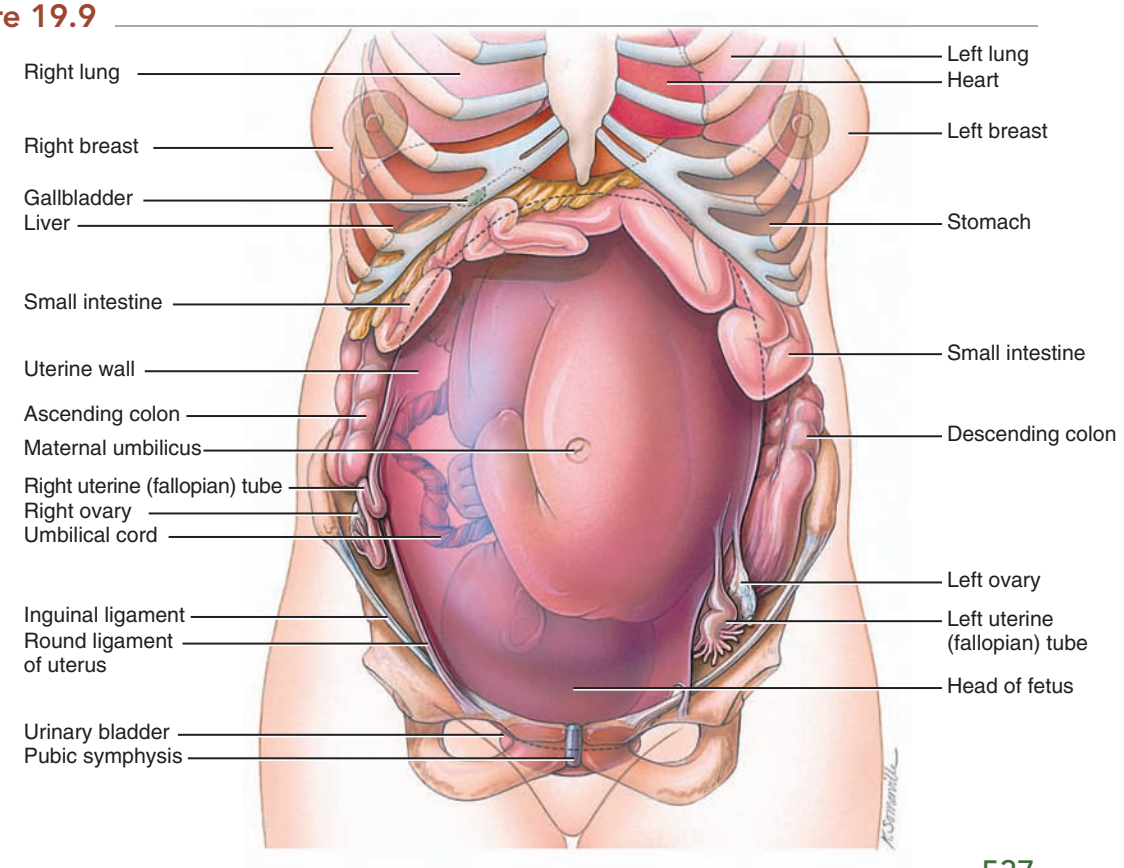
Fetal development, which begins at week 9 after conception, is a stage of rapid organ growth and maturation. The fetus begins this stage approximately 2.5 cm long, weighing about 1 gram. Within seven months, the fetus will grow to an average of 50 cm (20 in.) and weigh 3.75 kilograms (8 pounds). The pregnant woman's body will begin to show signs of the expanding uterus during the fetal stage. The fetus itself also begins to show signs of growth, becoming much more cramped in the confining uterus, as seen in **Figure 19.9**.

Fetal Circulation Is Unique

Wastes circulating in the fetus leave via the fetal blood moving through the placenta, where the wastes diffuse to the mother's capillaries. This process is carried out by simple diffusion, because the concentrations of waste materials are lower in maternal blood than in fetal blood. The fetal urinary system begins functioning early in the tenth week. Fetal urine is then the main source for replenishing the amniotic fluid, supporting and cushioning the fetus with large volumes of fluid. The volume of amniotic fluid rises throughout the pregnancy, peaking around week 33 at about 750 ml. This volume is regulated by absorption into the maternal bloodstream and by fetal "respirations" where the fetus swallows small volumes of amniotic fluid continually. Nutrients from the mother enter the fetal circulation across the placenta by diffusing down their concentration gradient just as fetal wastes leave by diffusing down theirs. Oxygen carried by the mother's hemoglobin

The fetus in utero • Figure 19.9

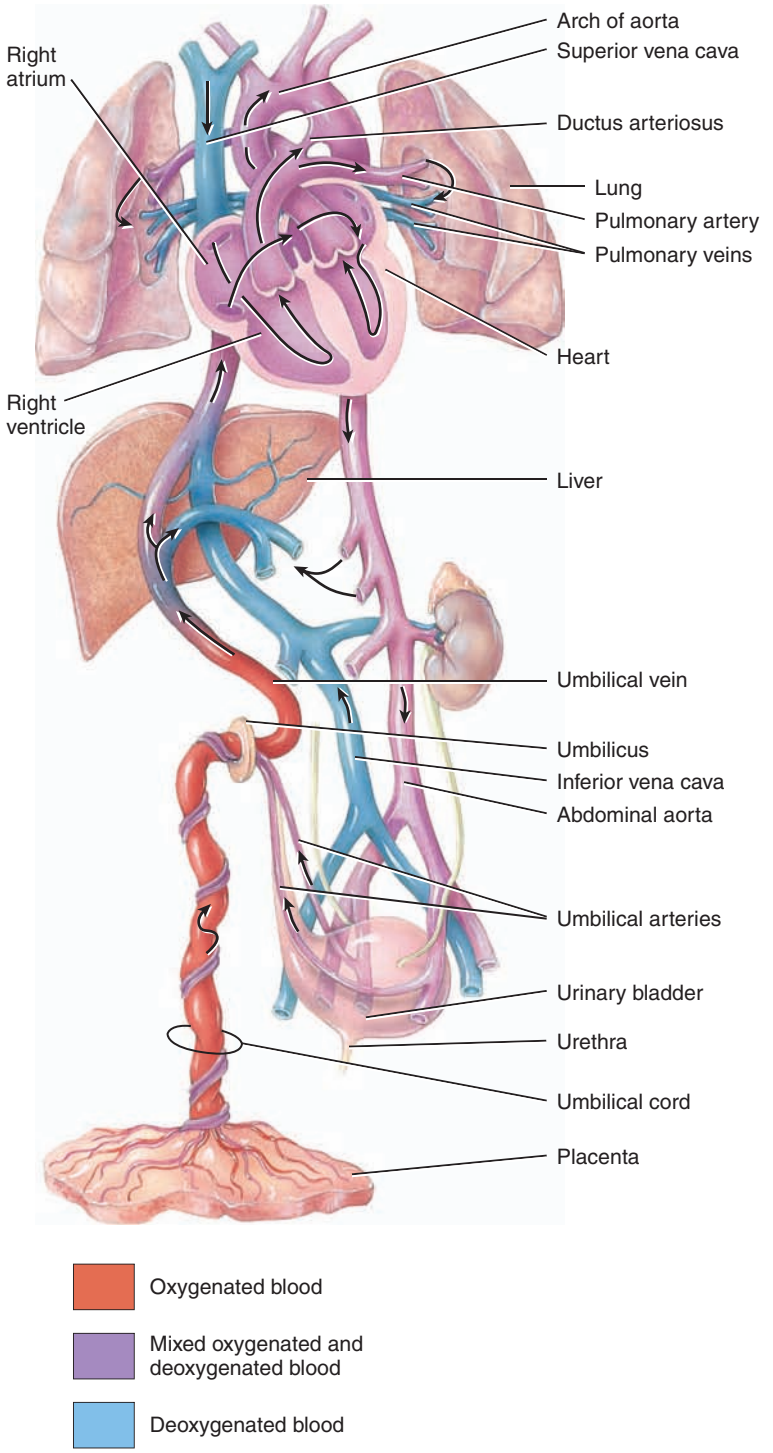
Have you ever heard that you can predict the gender of an unborn fetus by how high or how low the mother is carrying the baby? Not true. Equally false is the attempt to determine the gender by watching the swing of a penny on a string held above the mother's belly. Although on average a female fetus's heart does beat faster than a male's heart, it is not true that a fetal girl's heart rate is always faster than 140 or that a fetal boy's rate is always below 140. The most reliable noninvasive way to predict the gender of the baby uses an ultrasound device, which can usually provide visualization of the developing male sex organs.



Anterior view of position of organs at end of full-term pregnancy

Placental–fetal circulation • Figure 19.10

This image shows fetal circulation, beginning at the placenta and traveling via the umbilical vein through the fetal liver and on to the fetal heart. Note the hole between the right and left atria and the ductus arteriosus. Both permit blood to move from the pulmonary circuit to the fetal body, circumventing the not-yet-functional fetal lungs. Deoxygenated fetal blood and wastes are returned to the placenta via the umbilical arteries.



is literally stolen from the maternal hemoglobin by fetal hemoglobin, which has a higher affinity for the gas.

Fetal blood leaves the heart and moves through the umbilical arteries to the chorionic villi, where its associated gases and waste products diffuse with maternal blood, as seen in **Figure 19.10**. This chemically cleansed blood is then collected in placental veins and returned to the fetus through the single umbilical vein. The umbilical vein travels to the fetal liver, where it is dropped into the hepatic vein. All that remains of these vessels after birth is the **round ligament**, which marks the path of the umbilical vein from the navel to the liver and is visible in your belly button. The umbilical arteries dissolve soon after birth, adding to the hepatic capillary system.

Fetal Development Occupies the Second and Third Trimesters

Prenatal development and pregnancy is usually divided into **trimesters**. The first trimester includes all embryonic development and the first month of fetal development. By the end of the third month, the cartilage skeleton is starting to ossify, the kidneys and liver are functioning, teeth have formed, and external genitalia are clearly male or female.

trimester One of three 3-month periods during pregnancy.

The **second trimester** includes months 4, 5, and 6. Month 4 sees continued rapid changes, as the face begins to resemble its final form at birth. Blood cells are produced by the liver and bone marrow, and ovarian follicles are forming in the female ovaries. The fetus has grown from 2.5 to 15.3 cm in two months and has gained approximately 165 g. The nervous and muscular systems have developed enough that by the fifth month movements may begin. The mother may feel this **quickening** as fluttering or "butterflies" in her abdomen. At this point, you can hear the fetal heartbeat through a stethoscope placed on the distended abdomen. The fetal skin is covered in soft hair called **lanugo**. By the end of the sixth month, the fetus weighs approximately 450 g. With excellent and immediate medical care, it could survive outside the womb (we'll discuss the issue of prematurity later on). The lungs begin secreting **surfactant**, allowing the alveoli to inflate and deflate without their walls sticking together.

surfactant Detergent-like compound that prevents alveolar membranes from sticking together.

The **third trimester** is characterized by continued rapid growth and maturation. The eyes open and close, the sucking response develops (many fetuses begin to suck their thumbs or other fingers), and loud noises initiate a startle reaction. The fetus often moves regularly, perhaps looking for a comfortable position in the cramped womb. The lanugo is lost, and a layer of protective fat begins to develop. In males, the testes descend into the scrotal sac. See Figure 19.11 for a snapshot of the changes in the fetus from 13 to 26 weeks.

By the end of week 38, the fetus is prepared for life outside the uterus. It has maneuvered to a head-downward position, and "**dropped**." This means that the fetus is now resting on the cervix rather than filling the center of the uterus. Although the maternal stomach and lungs now have a bit more room, the fetus puts more pressure on the bladder and rectum, stimulating more frequent voiding. Nevertheless, the mother often feels some relief during the last week or two of pregnancy. Table 19.1 on the following page gives a summary of the important milestones of the embryonic and fetal development process.

Prenatal Analysis Helps Parents and Medical Professionals

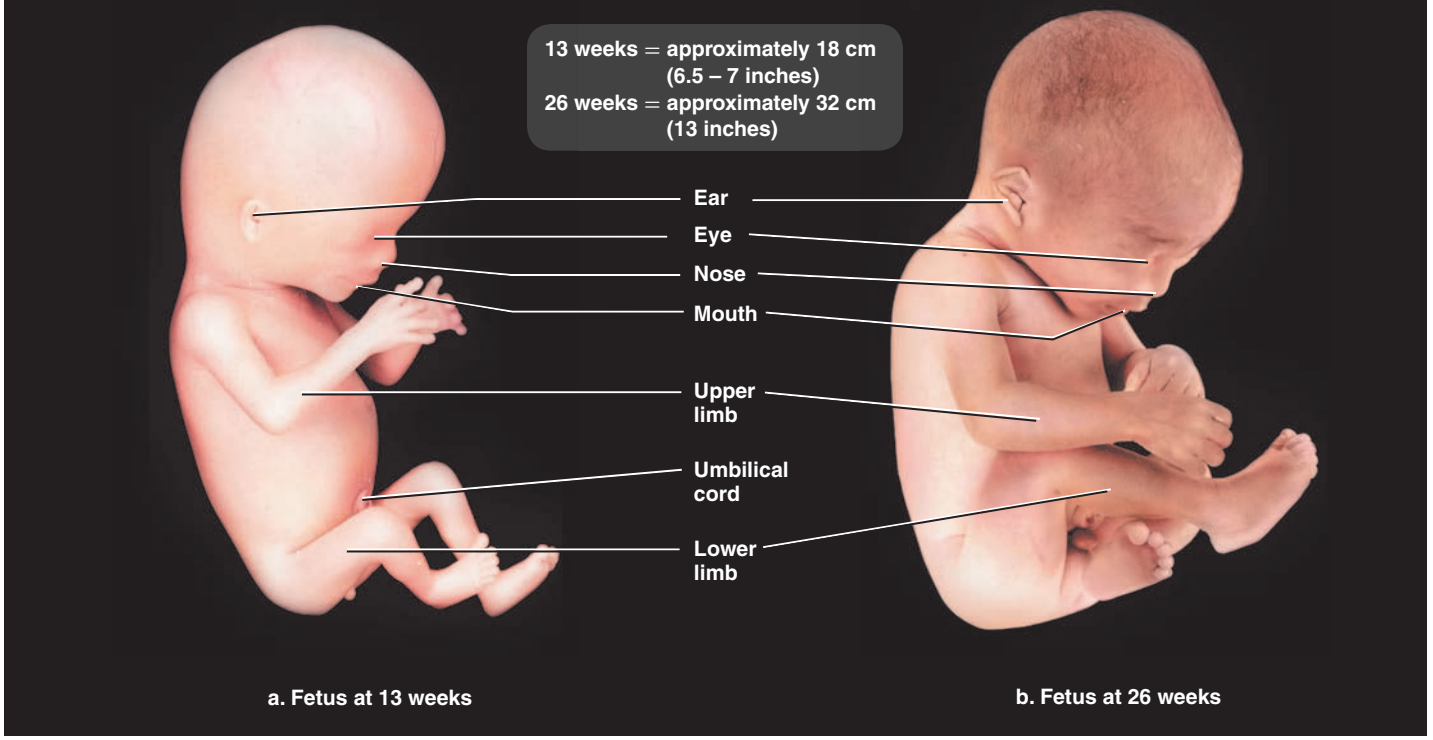
Throughout the pregnancy, medical professionals and the prospective parents want assurance that the future child is developing correctly. Technology provides many ways to "see" inside the uterus and gauge the health or even the gender of the baby-to-be. The **obstetric** visit at 18 to 20 weeks in the United States routinely includes an **ultrasound examination**. This exam can visualize many things. A close approximation of gestational age can be determined by measuring and comparing the size of various fetal body parts; the heart can be seen beating, and internal organs and the skeleton can be viewed. Often, even the gender of the developing fetus can be determined if it is in the right position. Birth defects, such as spina bifida, are also visible.

obstetrics The medical field devoted to prenatal and maternal care.

ultrasound examination Bouncing ultrasonic waves through the maternal skin into the uterus to observe the reflected patterns.

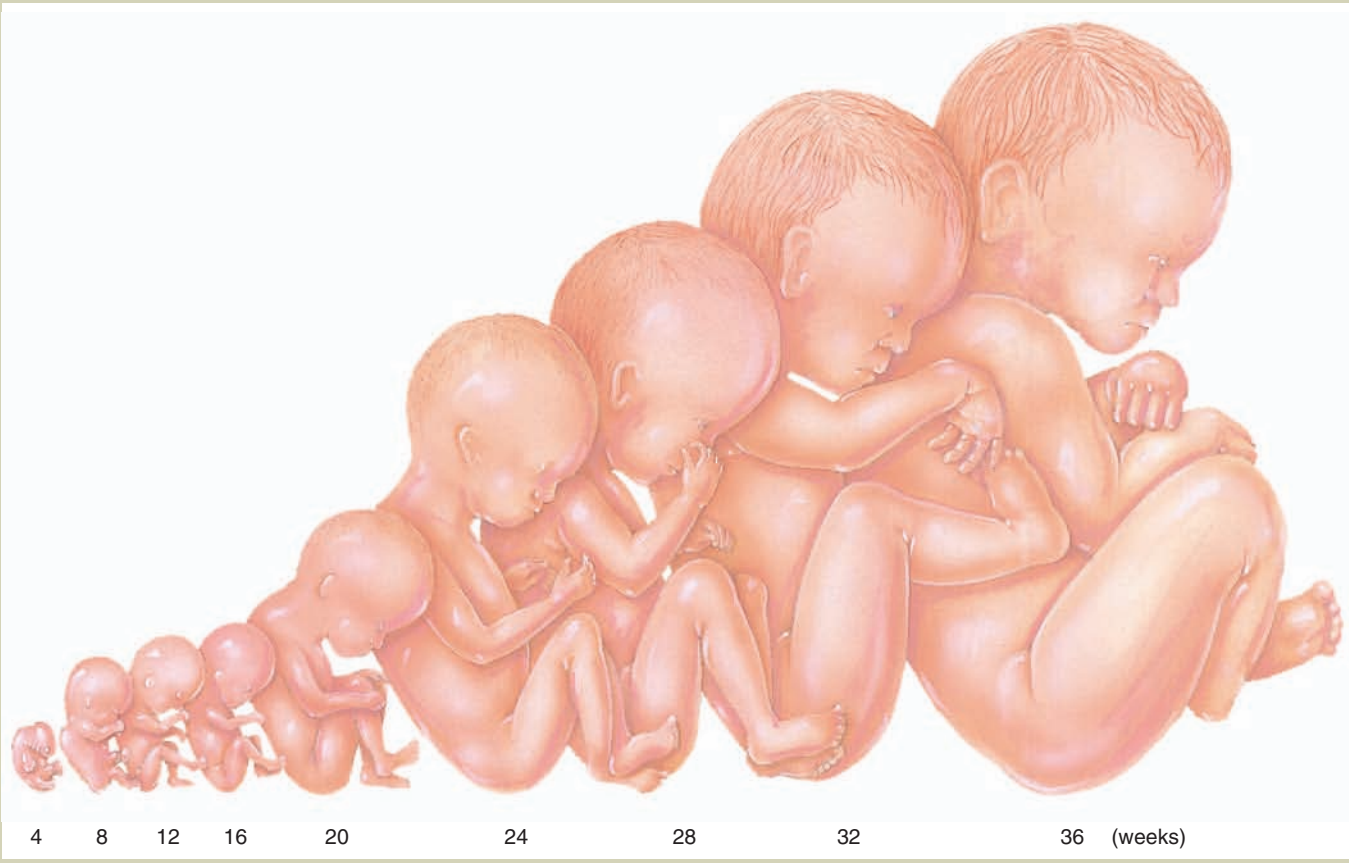
Two stages in fetal development • Figure 19.11

During the fetal period, not many new structures appear, but body growth is rapid. The head decreases in size in relation to the rest of the body, and the limbs increase in size. The 26-week-old fetus is less vulnerable to the effects of radiation or drugs than the 13-week-old fetus.



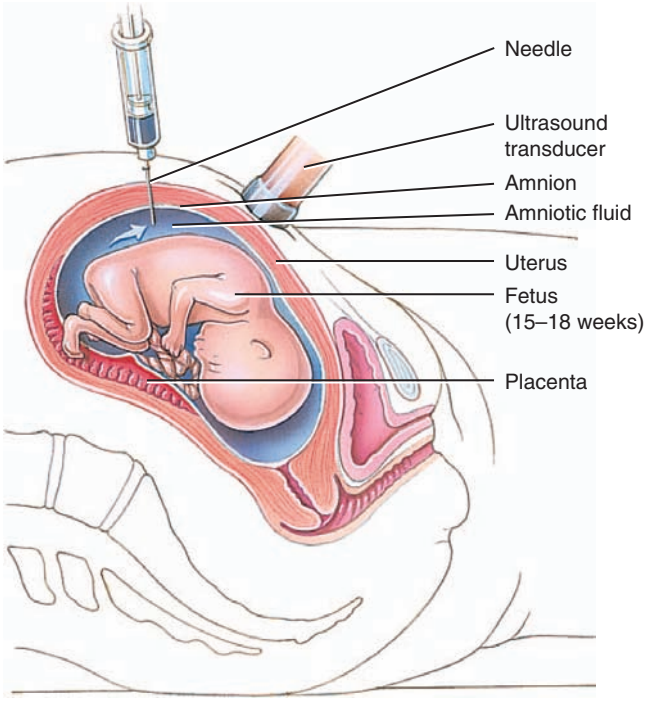
Developmental summary Table 19.1

Time	Approximate size and weight	Representative changes
Embryonic period (first 2 weeks are "early embryonic" period)		
1–4 weeks	0.6 cm (3/16 in.)	Primary germ layers and notochord develop. Neurulation occurs. Primary brain vesicles, somites, and intraembryonic body cavity develop. Blood vessel formation begins, and blood forms in yolk sac, allantois, and chorion. Heart forms and begins to beat. Chorionic villi develop, and placental formation begins. The embryo appears. The primitive gut, pharyngeal arches, and limb buds develop. Eyes and ears begin to develop, tail forms, and body systems begin to form.
5–8 weeks	3 cm (1.25 in.) 1 g (1/30 oz)	Primary brain vesicles develop into secondary brain vesicles. Limbs become distinct and digits appear. Heart becomes four chambered. Eyes are far apart, and eyelids are fused. Nose develops and is flat. Face is more human-like. Ossification begins. Blood cells start to form in liver. External genitals begin to differentiate. Tail disappears. Major blood vessels form. Many internal organs continue to develop.
Fetal period		
9–12 weeks	7.5 cm (3 in.) 30 g (1 oz)	Head constitutes about half the length of the fetal body, and fetal length nearly doubles. Brain continues to enlarge. Face is broad, with eyes fully developed, closed, and widely separated. Nose develops a bridge. External ears develop and are low set. Ossification continues. Upper limbs almost reach final relative length, but lower limbs are not quite as well developed. Heartbeat can be detected. Gender is distinguishable from external genitals. Urine secreted by fetus is added to amniotic fluid. Red bone marrow, thymus, and spleen participate in blood cell formation. Fetus begins to move, but its movements cannot yet be felt by the mother. Body systems continue to develop.
13–16 weeks	18 cm (6.5–7 in.) 100 g (4 oz)	Head is relatively smaller than rest of body. Eyes move medially to their final positions, and ears move to their final positions on the sides of the head. Lower limbs lengthen. Fetus appears more human-like. Rapid development of body systems occurs.
17–20 weeks	25–30 cm (10–12 in.) 200–450 g (0.5–1 lb)	Head is more proportionate to rest of body. Eyebrows and head hair are visible. Growth slows, but lower limbs continue to lengthen. Vernix caseosa (fatty secretions of oil glands and dead epithelial cells) and lanugo (delicate fetal hair) cover fetus. Brown fat forms and is the site of heat production. Fetal movements are commonly felt by mother (quickening).
21–25 weeks	27–35 cm (11–14 in.) 550–800 g (1.25–1.5 lb)	Head becomes even more proportionate to rest of body. Weight gain is substantial, and skin is pink and wrinkled. By 24 weeks, alveolar cells begin to produce surfactant.
26–29 weeks	32–42 cm (13–17 in.) 1,110–1,350 g (2.5–3 lb)	Head and body are more proportionate, and eyes are open. Toenails are visible. Body fat is 3.5% of total body mass, and additional subcutaneous fat smoothes out some wrinkles. Testes begin to descend toward scrotum at 28 to 32 weeks. Red bone marrow is major site of blood cell production. Many fetuses born prematurely during this period survive if given intensive care, because lungs can provide adequate ventilation and central nervous system is developed enough to control breathing and body temperature.
30–34 weeks	41–45 cm (16.5–18 in.) 2,000–2,300 g (4.5–5 lb)	Skin is pink and smooth. Fetus assumes upside-down position. Pupillary reflex is present by 30 weeks. Body fat is 8% of total body mass. Fetuses 33 weeks and older usually survive if born prematurely.
35–38 weeks	50 cm (20 in.) 3,200–3,400 g (7–7.5 lb)	By 38 weeks, circumference of fetal abdomen is greater than that of head. Skin is usually bluish-pink, and growth slows as birth approaches. Body fat is 16% of total body mass. Testes are usually in scrotum in full-term male infants. Even after birth, an infant is not completely developed; an additional year is required, especially for complete development of the nervous system.


4
8
12
16
20
24
28
32
36
(weeks)

Amniocentesis • Figure 19.12

In this procedure, a needle goes through the uterine wall into the amniotic sac, under the guidance of ultrasound equipment, and less than an ounce of amniotic fluid is extracted for testing. There is a very slight risk that the needle puncture may not heal properly or that some other complication can arise because of the procedure, but the test results are extremely accurate.



Amniocentesis and chorionic villus sampling provide key data. Information on the genetic health of the fetus is available through **amniocentesis** or **chorionic villus sampling**. As the embryo and fetus develop, cells are lost to the amniotic fluid. Amniocentesis, the collection of amniotic fluid for analysis, is shown in Figure 19.12. Amniocentesis is performed at 15 to 18 weeks to determine gender and the condition of the chromosomes.

Using ultrasound, the physician guides a needle into the amniotic fluid, being careful not to touch the fetus with the sharp end. A sample of amniotic fluid along with cells shed from the baby's skin is withdrawn and analyzed. The DNA within these cells is isolated, and a **karyotype** is created. Abnormalities, such as trisomy 21 (Down syndrome) or Klinefelter's syndrome (XXY chromosomes, causing a phenotypically male individual with enlarged breasts and female fat deposits) can be seen immediately.

karyotype A micrograph of the chromosomes, arranged to show chromosome pairs.

Chorionic villus sampling is used to detect genetic anomalies earlier in the pregnancy. In this test a small bit of the chorion is removed, usually between weeks 10 and 12—early enough to allow for an abortion if a serious defect is detected.

There is a newcomer to prenatal analysis. A newcomer to prenatal analysis, called 4D ultrasound, is becoming available. This computer-enhanced ultrasound produces a clear, lifelike view of the fetus. Movement can be seen as if the fetus was outside the womb, and facial features are much clearer. A few intriguing studies have shown that the father bonds much more strongly with his baby-to-be when he can clearly see the baby's face.

CONCEPT CHECK

STOP

1. **Why** does fetal circulation differ from neonatal circulation?
2. **Which** events characterize the second and third trimester of development?
3. **What** is chorionic villus sampling? **When** is it used in place of amniocentesis?
4. **What** are the developmental changes that precede birth?

19.4 Labor Initiates the End of Pregnancy

LEARNING OBJECTIVES

1. **Describe** the hormonal controls on labor, and the stages of labor.
2. **Describe** the complications the fetus may encounter during labor.
3. **Explain** the functioning of the mammary glands after birth.

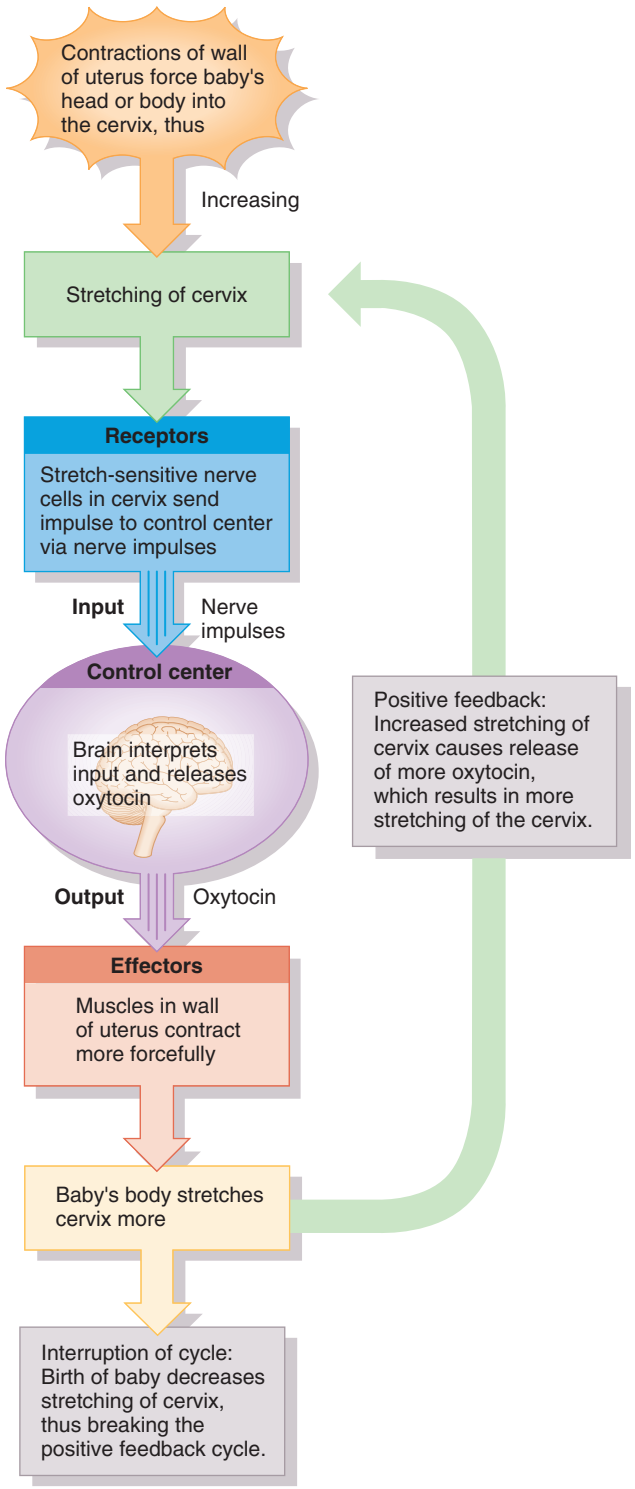
Labor and **birth** mark the end of prenatal life and of total reliance on the mother. The fetus goes from an aqueous environment with total life support to a dry environment where all life functions must come from within. Organ systems switch from standby status, or limited functioning, to the full-speed-ahead status they will occupy for the rest of their life span. The lungs, for example, must start exchanging gases before the umbilical cord is severed. The digestive system must start to work after the first suckle of milk. The heart must be able to pump blood against pressure. The skin must protect the body from damage, and fat layers must help maintain internal temperature.

Labor Begins with Hormonal Triggers

Before any of this takes place, the fetus must be expelled from the uterus. Labor begins with hormonal triggers that are thought to originate in the fetal pituitary gland. The fetal **anterior pituitary gland** secretes **ACTH**, which triggers the fetal adrenal glands to secrete hormones that affect the placenta. The placenta increases production of estrogen and decreases production of progesterone. Estrogen increases **oxytocin** receptors on the placenta and increases placental **prostaglandin** production. This combination of factors makes the uterus much more sensitive to oxytocin levels. Maternal oxytocin then initiates rhythmic contractions in the uterus.

In a rare example of positive feedback in a healthy human, contractions of the uterus stimulate oxytocin production. More oxytocin means more and harder contractions, which in turn means more oxytocin. The contractions become stronger, harder, and closer together. Most first births take 24 hours from initial contractions to delivery. Subsequent births generally move much faster. Figure 19.13 shows the positive feedback system at work.

Positive feedback control of labor contractions • Figure 19.13



Delivery Has Three Stages

The three stages of delivery—dilation, expulsion, and placental—are summarized in **Figure 19.14**. The first stage is **dilation**. The fetal head presses on the cervix. This pressure, combined with uterine contractions, stretches the cervical opening, which increases with each uterine contraction, going from slightly less than 2 cm to over 10 cm. As the opening enlarges, the mucus plug that was created by placental hormones drops out. The thin amnion is all that remains between the fetus and the external environment. This fragile membrane ruptures under increasing pressure, releasing a rush of amniotic fluid (often referred to as the "water breaking"). After the amniotic fluid is lost, labor begins in earnest. Because the fetus is now subjected to the external environment without any protective fluid surrounding it, it is imperative that the baby be born within 24 hours. If true labor does not begin within that time, labor will be induced (artificially started) using injections of labor-inducing hormones.

dilation The act of expanding or being expanded.

Expulsion is a shorter stage.

The second stage of delivery, **expulsion**, is relatively short, usually lasting less than an hour. Expulsion is the time from full cervical dilation to delivery. Uterine contractions gain strength, and the mother experiences an overpowering desire to assist in the birth by pushing with voluntary muscles. With all this additional pushing, the baby moves through the cervix and out the vagina. Once the head **crowns**, or pushes through the opening of the vagina, the baby is on its way. A birthing attendant will help the baby breathe by suctioning mucus from the mouth and nose, even before the birth is completed. Once the baby's head is clear, the body slips out surprisingly quickly. The umbilical cord is clamped and then cut. The baby is now on his or her own, with no support from the maternal organs.

expulsion The act of forcing out.

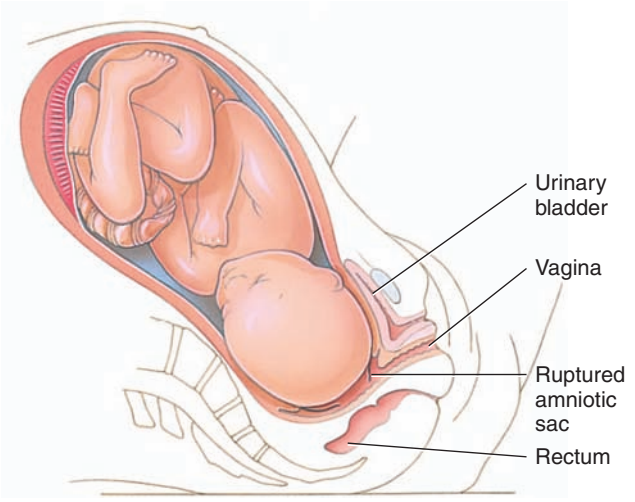
The placenta and umbilical cord are expelled in the final stage.

The final stage of labor is the **afterbirth** or **placental stage**. The placenta is still in the uterus. As mentioned, the placenta is a disposable organ, and with the birth of the fetus, its utility is now over. Strong uterine contractions continue, and they tear the placenta from the walls of the now shrinking uterus.

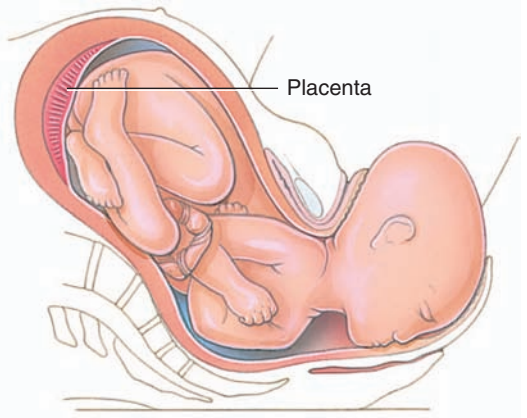
The placenta and its attached umbilical cord are expelled through the birth canal and checked by medi-

Stages of labor • Figure 19.14

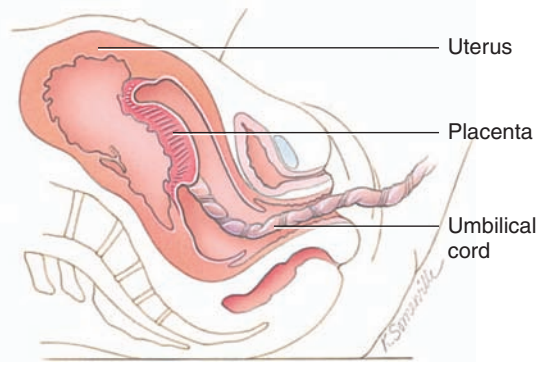
Dilation is the longest stage of labor, as the cervix opens from less than 2 cm to over 10 cm. The expulsion stage is also called the pushing stage, as uterine contractions gain strength and frequency. Expulsion is highlighted by the fetal head "crowning" and the baby's airways being cleared. Minutes after the baby's birth, the placenta follows.



1 Dilation



2 Expulsion



3 Placental stage

cal personnel. The arrangement of the placental vessels may suggest the presence of congenital defects. The maternal and fetal surfaces of the placenta also show whether the entire organ has been expelled. Any pieces of placenta left in the uterus could become infected, causing life-threatening maternal septicemia if not removed. Some parents have parts of the placenta frozen as a potential source of stem cells that may be useful in treating serious illnesses in their child years afterward.

Fetal Development Can Have Many Complications

Labor and delivery usually follow the same general pattern, but complications can require medical intervention. Some babies leave the sheltering environment of the uterus too soon. A **premature baby**, or a preemie, is defined as one born before 37 weeks of gestation (a full-term baby spends 37 to 42 weeks in utero). Preemies are usually quite small, and their organ systems are immature. They require specialized care in neonatal intensive care units until their organs have matured. The duration of care and the severity of the situation depend on the degree of prematurity. Typical complications include respiratory distress syndrome, occasional cessation of breathing, inability to suck or swallow due to an immature nervous system, nutrient intolerance due to immature gastrointestinal lining, and improper blood filtration due to immature kidneys. For more on preemies, see *What a Scientist Sees: Prematurity—How Young Is Too Young?*

The number of premature infants born before 37 weeks reached 12.5% of births in the United States in 2003. Reasons for this increase remain unclear, but according to the March of Dimes, many medical professionals believe industrial chemicals, pesticides, poor standards of living, and air pollutants are to blame. Others suggest

WHAT A SCIENTIST SEES

Prematurity—How Young Is Too Young?

THE PLANNER

For a human fetus, the uterus is the optimum environment. Physically sheltered, warmed by the mother, protected by her skin and antibodies, and nourished by organic compounds in her blood, the fetus finds the womb to be the perfect "home." However, the fetus can be forcibly evicted, causing premature birth.

A variety of conditions can cause prematurity. Stress to the mother or fetus from many factors including illness or ingested compounds can give rise to corticotropin-releasing hormone, which may trigger other hormones that cause premature uterine contractions and delivery.

A week or two of prematurity is nothing serious. Beyond that, however, critical considerations arise. The medical specialty of neonatology has arisen to care for premature babies who are usually sheltered in neonatal intensive care units (NICUs). The field has made major strides in the past few decades, but as younger infants are routinely saved in NICUs, new problems arise. One recent concern is the effect of isolation, used to prevent infection and help the young lungs do their job. Many preemies spend weeks isolated in incubators. Studies of NICUs show that "procedural touch" used to sustain the baby can disturb the child physically and psychologically. "Comforting touch" and massage are now added to the NICU care-giving routine.

However, as medicine gains the ability to save ever-younger preemies, is there a point at which rehabilitation no longer makes sense?

Think Critically

1. What are some of the health issues that arise as younger premature infants are saved?
2. Where is the limit beyond which NICU no longer makes sense?
3. Who should decide whether the costs of care and possible resulting persistent medical problems of the saved individual outweigh the potential benefits of saving the child?

that as women become pregnant later in life, premature births are more likely. In some cases, medical conditions, such as placenta previa, may require an early delivery, but in general, full term is desirable. Infants who are only moderately premature (34 to 36 weeks) have a threefold greater infant mortality rate, have higher medical costs, and spend more time in neonatal intensive care units. They also return to the hospital more frequently than full-term babies. Among highly preterm babies (less than 32 weeks gestation), the risk of death and long-term disabilities soars. These disabilities may include mental retardation, cerebral palsy, lung and gastrointestinal problems, and vision and hearing loss.

Labor must be induced in some cases. Sometimes it seems as though the baby just does not want to leave the womb. If there is no sign of labor after 42 weeks of development, the obstetrician will often induce labor. Although we still do not completely understand the hormonal controls on labor, we do know that increased levels of oxytocin initiate uterine contractions. To induce labor, the mother usually gets intravenous injections of a synthetic form of oxytocin called pitocin. Commonly called a "pit drip," the intravenous pitocin pushes the uterus into strong contractions, beginning dilation and labor almost immediately.

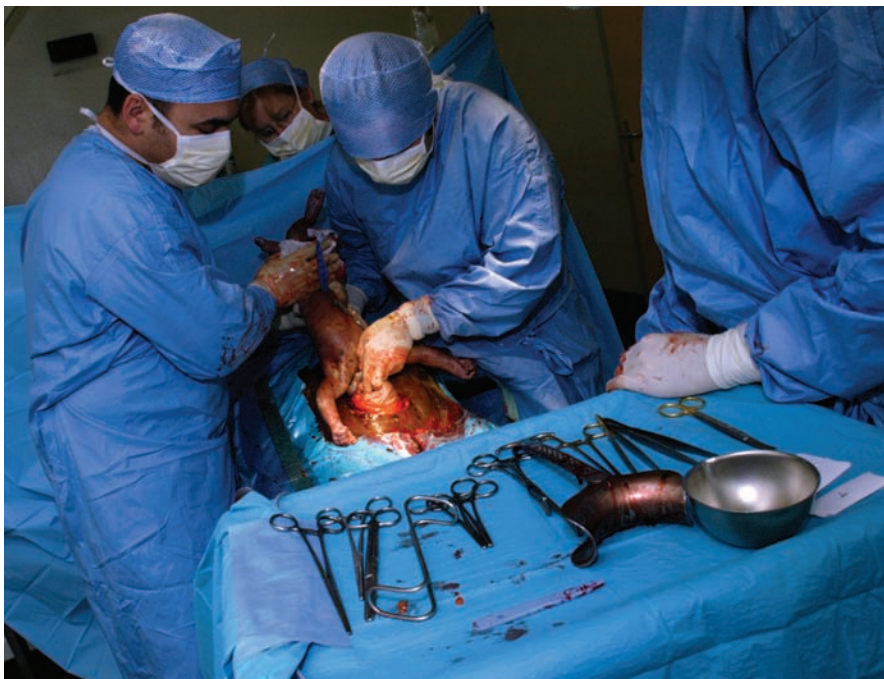
The baby's position in the womb can be a complication. The timing of labor may be a source of complication in the whole delivery process. Another complication associated with birth concerns the baby's position in the womb. A "breech baby" has the buttocks or feet below the head, which normally pushes the cervix open. Medical personnel can try to turn the baby using internal and external manipulations or can perform a cesarean delivery. Internal manipulation, using giant tongs called forceps, is an option for the mother who does not want a cesarean delivery. This procedure can harm the baby, so forceps are used only after careful consideration. External manipulation involves putting pressure on the fetus through the maternal abdomen to try to shift the fetal position. Often, fetuses in the breech position can be "turned" using gentle pressure from outside the uterus. The fetus will move its limbs, pressing back against the external pressure. If applied correctly, the fetus may turn itself in response to the gentle pressures from the physician.

A cesarean delivery may be needed. A cesarean delivery may be used when the baby cannot be delivered naturally—if, for example, the baby's head is too large to fit through the mother's pelvis—and for emergency deliveries, when the baby is in distress due to lack of oxygen. A surgeon opens the maternal skin and uterus, lifts the baby out, examines the uterus, and removes all afterbirth. **Figure 19.15** shows a baby moments after a cesarean birth. The oral cavity of the fetus is suctioned out to remove mucus and amniotic fluid that is normally removed while the baby is squeezed through the birth canal.

Some infants fail to gain weight. Another type of difficulty, called *failure to thrive*, can begin shortly after birth. Some infants and children fail to gain weight like others of their age. Because so many factors can affect growth and development, quick diagnosis is critical. At every doctor's visit, the infant is weighed and measured, and these numbers are plotted on a chart and compared to national standards. If there is cause for concern, medical, economic, social, and psychological factors should be investigated. Medical causes of failure to thrive include chromosomal defects, endocrine abnormalities, anemia, or malformed gastrointestinal organs. Economic and social causes are similar to those that are linked to high rates of prematurity and include poverty, parental neglect, poor eating habits, or exposure to toxic environments. Psychological factors include emotional deprivation and parental abuse.

Cesarean birth • Figure 19.15

Here doctors have performed a cesarean section, removing a baby from the uterus through the abdominal wall rather than through the birth canal. This is usually done when the baby cannot fit past the pelvic bones or when the baby or mother is in mortal danger due to some difficulty with the natural birthing process.



Ambiguous sex determination arises out of hormonal imbalances. The spectacularly complicated timing and choreography of hormones, cell divisions and growth, and organ and tissue development can lead to extraordinary events, including one that has been termed ambiguous sex determination or "intersexuality." See *Ethics and Issues: How Do We Respond to Intersexuality?* for more on this.

ETHICS AND ISSUES

THE PLANNER

How Do We Respond to Intersexuality?

You are pregnant. Do you want a boy or a girl?

The socially correct answer is, "Either, as long as it's healthy."

What if your healthy baby is neither boy nor girl? Or both a boy and a girl?

That situation is what approximately 1,000 couples each year in the United States face when their newborn turns out to be what doctors term *intersex*. An intersex birth occurs when a fetus's genetic and hormonal characteristics are out of sync.

A fetus is bombarded with large doses of sex hormones. These hormones cause the development of internal and external sexual organs. Most of the time, those organs reach their "proper" size by the time the infant is born. However, if any hormonal "blast" is not large enough, or if the wrong sex-defining hormone is present, the result will be "ambiguous genitalia." These may include testes and/or fused labia (no vaginal opening) in a genetic female or a clitoris-sized "micropenis" in a genetic male.

Until the 1950s, children born with ambiguous genitalia were left alone. Known as hermaphrodites and sterile because of their medical condition, they did not reproduce. Many were shunned by family and friends and lived solitary lives. Some became the "she males" of circus sideshows and boardwalk freak shows.

Beginning in the 1950s, with the development of improved surgical techniques, efforts were made to assign a sexual identity to infants with ambiguous genitalia. More often than not, because of the relative ease of surgically creating female genitalia, the infant was assigned a female identity.

Sex assignment was pioneered by psychologist John Money at Johns Hopkins University in Baltimore. Money was a proponent of the theory that all children are "blank slates" at birth and therefore any child can be raised as either a girl or a boy. William Reiner, a psychiatrist and urologist who worked with Money and still treats numerous intersex individuals, told the Public Broadcasting Show *Nova* in its 2001 episode "Sex: Unknown" that surgeons and psychologists thought: "We have a surgical solution because we have a psychological solution. We can construct the child as a female and your child will grow up to be a successful, happy girl or woman." As we have since learned, Dr. Money's theories were tragically flawed. His most famous case study on gender reassignment was misreported, and in fact ended in tragedy for the patient and his twin sibling. The sibling died of a drug overdose at an early age, and the patient whose gender was reassigned eventually committed suicide. The boys' parents blamed Dr. Money for both siblings' deaths.

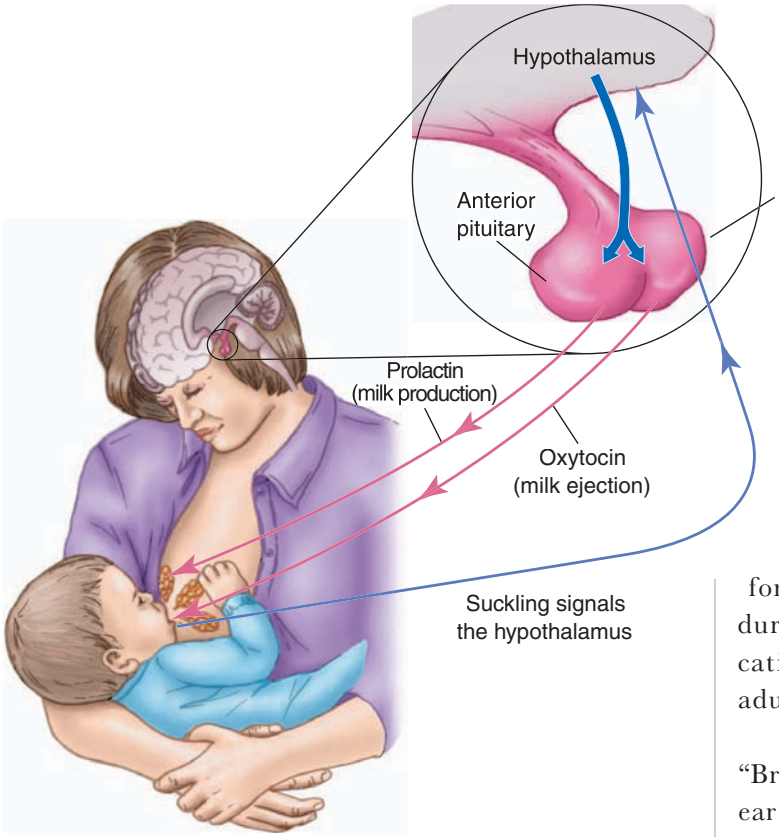
Biologists argued that a child's upbringing could not overcome the effects of naturally occurring hormones. Despite the problem of hormonal/genetic mismatch that occurred during gestation, an intersex individual who is a genetic female continues to produce estrogen; similarly, a genetic male continues to produce testosterone; these hormones affect the functioning of the hypothalamus. This argument gained further support in the 1990s, when scientists using sophisticated imaging technologies to map the brains of male–female transsexuals discovered differences between the brains of men and women. Brains are either male or female, too!

Critical Reasoning Issues Today, heightened awareness of biological gender differences, the politicization of gender identity, and the increasingly public resentment of many individuals who were assigned a female identity at birth have all led to changes in the protocol for dealing with intersex children. However, there is still disagreement over the proper course of action.

Think Critically

1. Should surgery on an intersex child be delayed until the child has developed a gender identity?
2. If the genital anomalies involve life- or health-compromising problems, should an intersex child receive surgery accompanied by hormonal treatment to complement the surgically constructed genitals, or should hormonal treatment be delayed until the child has established a gender identity, allowing for the possibility of reassignment?

Hormonal controls on the mammary gland • Figure 19.16



The Mammary Gland Provides Milk When Needed

The neonate must obtain nutrients via the digestive system immediately after birth because the placenta is no longer supplying nutrients. The mother continues to nourish the infant, but now that nourishment comes in the form of milk produced by the mammary glands. Each breast contains approximately 20 milk-producing lobules. These lobules are inactive until pregnancy, when they grow in size and number. The lobules end in ducts that drain to the nipple. No milk is produced until after birth, when prolactin is secreted by the anterior pituitary gland, causing the enlarged mammary glands to secrete milk. Figure 19.16 summarizes the hormonal controls on the mammary glands.

The first substance produced by the mammary gland appears for two or three days after delivery. This watery fluid, called **colostrum**, is rich in proteins and antibodies. Actual milk production requires the infant to suckle the breast, which stimulates the areola and starts the release of oxytocin from the hypothalamus. Oxytocin stimulates the "let-down response," causing contractions of the larger **lactiferous ducts**.

Breastfeeding is a personal choice, with products available now that can replace natural milk if the mother so chooses. However, there are benefits to breastfeeding, as noted even on the labels of most commercial infant formulas. Breastfeeding promotes bonding between mother and infant. Antibodies and lymphocytes present in breast milk, but not in baby formula, help protect infants from numerous diseases during the first months of life. There are some indications that these health benefits may last well into adult years.

According to the U.S. Food and Drug Administration, "Breastfed infants have lower rates of hospital admissions, ear infections, diarrhea, rashes, allergies, and other medical problems than bottle-fed babies. Breastfed babies are protected, in varying degrees, from a number of illnesses, including pneumonia, botulism, bronchitis, staphylococcal infections, influenza, ear infections, and German measles. Furthermore, mothers produce antibodies to whatever disease is present in their environment, making their milk custom-designed to fight the diseases their babies are exposed to as well."

CONCEPT CHECK STOP

1. **How** do hormones control labor, and **what** are the stages of delivery?
2. **What** complications might the fetus encounter during labor?
3. **How** do the mammary glands function after birth?

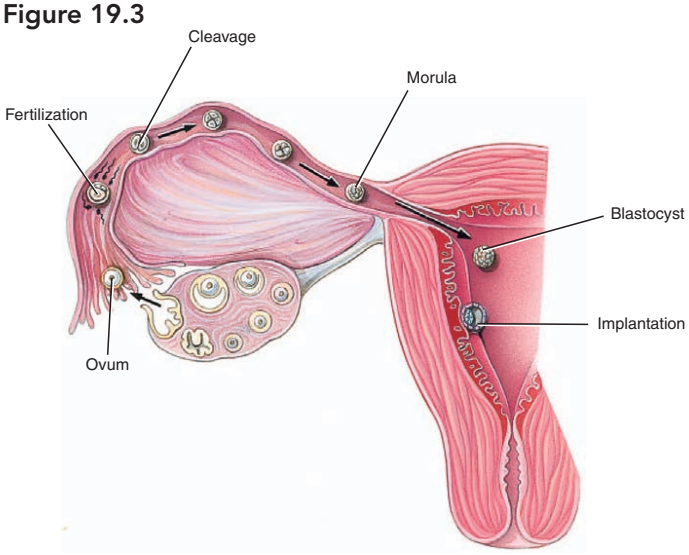
Summary

THE PLANNER

1 Days 1 Through 14 Include Fertilization and Implantation 524

- New life begins as sperm DNA fuses with egg DNA. The sperm travel up the female tract, propelled by muscular contractions of the female organs as well as the sperm's flagellum.
- During the trip the sperm become capacitated, activating the acrosomal enzymes. Although many sperm may bind to the zona pellucida receptors of an egg, only one sperm can enter the ovum cytoplasm and create a zygote.
- The zygote travels down the rest of the uterine tube, undergoing cleavage to form a morula and then a blastocyst.
- As shown here, by day 7, the blastocyst has entered the uterus and settled into the endometrium. In the next 24 hours, the blastocyst implants more permanently, as the trophoblast digests the endometrial tissue. The uterine lining thickens in the area where implantation occurs, and the chorion is developed. The beginnings of the embryo and supporting structures are created as the inner cell mass divides.

Figure 19.3



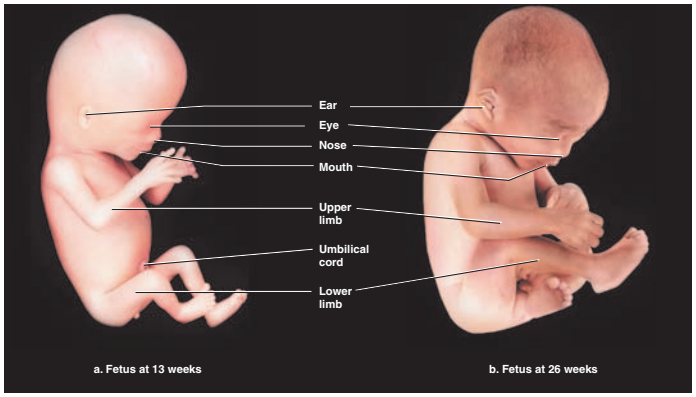
2 The Embryonic Stage Is Marked by Differentiation and Morphogenesis 531

- The **embryonic** disc and the amnion form from the inner cell mass. Soon, the yolk sac, amnion, chorion, allantois, and the embryo **differentiate**. These tissues will become the **extraembryonic** membranes as well as the embryo itself.
- The **umbilical cord** develops, suspending the developing embryo in the amniotic fluid while still maintaining contact with the blood exchange areas of the placenta. At the end of the embryonic stage, all major organs are in place, and the embryo looks distinctly human.

3 Fetal Development Is a Stage of Rapid Organ Growth 537

- Fetal development starts at the end of the first **trimester**, as the organs enlarge and begin functioning.
- The fetus, shown here, will grow to an average of 50 cm (20 in.) and gain approximately 3.75 kg (8 lb). A huge amount of metabolic activity accompanies this growth. With difficulty, the fetus could live outside the womb by the end of the second trimester, but premature delivery is definitely to be avoided if possible. By the seventh month, **surfactant** is produced by the lungs, making life outside the womb easier.

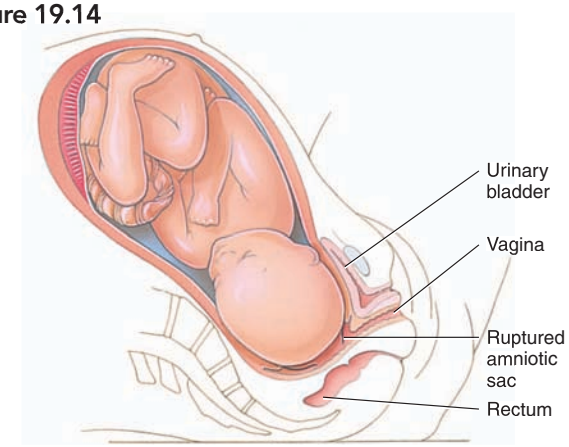
Figure 19.11



4 Labor Initiates the End of Pregnancy 543

- Labor starts at the end of pregnancy. It is believed that the fetal anterior pituitary gland initiates a positive feedback mechanism that leads to birth.
- The uterus becomes more susceptible to oxytocin, and as oxytocin levels increase in the maternal blood, the uterus begins to contract. Harder contractions stimulate production of more oxytocin, until the fetus is **expelled** and the uterus shrinks to almost normal size.
- Labor includes **dilating** the cervix, shown here, expelling the fetus, and passing the placenta.

Figure 19.14



Key Terms

- amniotic cavity 530
- cleavage 526
- differentiation 526
- dilation 544
- early embryonic 524
- ectoderm 531
- embryonic 524
- endoderm 531
- expulsion 544
- extraembryonic 532
- fetal 524
- germ cell 533
- interstitial fluid 532
- karyotype 542
- mesoderm 532
- morphogenesis 526
- obstetrics 539
- polyspermy 526
- surfactant 538
- trimester 538
- ultrasound examination 539
- umbilical cord 533
- viable 526

Critical and Creative Thinking Questions

1. The entire process of development in the womb can be confusing without a clear time line of activities. Return to the discussion of fertilization and embryonic development, and create such a time line. Indicate the order of events, beginning with the fusion of the male and female pronuclei and ending at the end of week 8.
2. Compare amniocentesis, chorionic villus sampling, and ultrasound. What are the strengths and weaknesses of each? Why is ultrasound routine but not amniocentesis or chorionic villi sampling?
3. In the early months of pregnancy, most women experience the need to frequently urinate. They can eat only small meals by the eighth month, and the need for frequent urination returns in the ninth month. Breathing is also hindered in the seventh and eighth months, but may return close to normal in the ninth month. Sketch the approximate size of the uterus at each trimester. Which organs are pushed out of place at each stage? Why the change in the last month?
4. **CLINICAL CLICK QUESTION**
   Kathleen was a healthy young women, who exercised regularly and ate fairly well. When she became pregnant, she continued her healthy lifestyle. She had no complaints other than feeling tired and hungry almost constantly, with slight nausea during the first few weeks. As the pregnancy advanced, her hunger seemed to grow as well. She experienced bouts of shaking and light-headedness before she ate, and she felt the need to eat more often during the day. Even with all this eating, her weight did not increase as the obstetrician hoped. Blood tests were run, looking for elevated levels of glucose.

   What is the endocrine disease that the obstetrician suspects Kathleen is suffering from? What might have caused her to develop this during pregnancy?

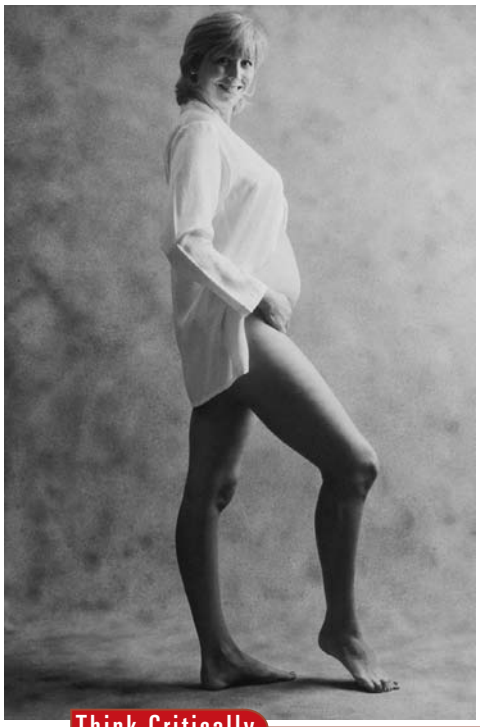
One of the hallmarks of this disease is elevated blood glucose. While her high blood glucose levels will not cause birth defects this late in the pregnancy (after week 28), it will affect the fetus. Glucose crosses the placenta. If there is a larger amount of glucose in the maternal blood, it follows that there will be higher levels of blood glucose in the fetus. What effects will this have this on the fetus?

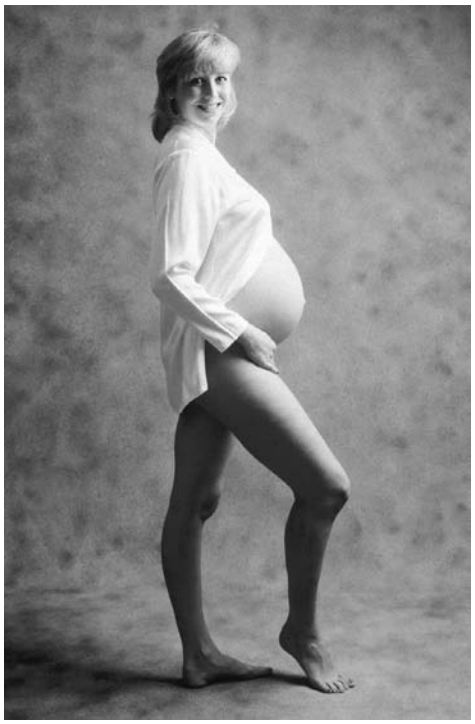
For help answering these questions, visit http ://www.diabetes.org/diabetes-basics/gestational/

5. At birth, the fetus transitions from an aqueous life protected in the womb to an arid, unprotected life in the atmosphere. What cardiovascular and respiratory changes must occur for the baby to survive this transition? Review fetal circulation online, and include the proper terminology for these changes. What other systems must now function to protect the infant?

What is happening in this picture?

Obviously, the woman in this series of images is pregnant. During this process, she has had another life struggling to survive within her body. Once the embryo successfully implanted in her endometrium, she has directly provided all the nutrients and oxygen necessary for this new life to develop. She has also provided protection, support, and possibly even comfort in the muted sounds of her voice as the embryo and—later—fetus grew closer to self-sufficiency. The demands of pregnancy take a toll on the female's physiology.





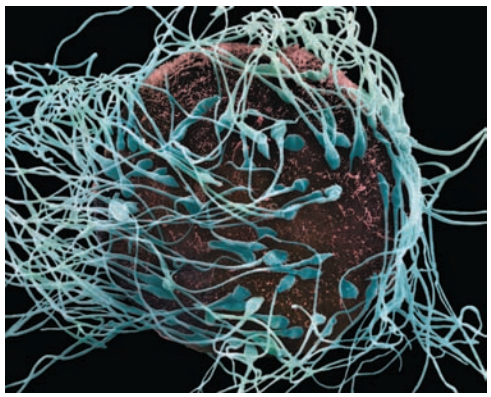
Think Critically

1. As the embryo implants and the placenta is formed, the woman may have experienced morning sickness. List the physiological changes that are occurring in the woman during this period. Specifically, what might be causing her nausea and discomfort?
2. In the second and third trimesters, the fetus is rapidly gaining weight. What new physiological demands are made of the woman at this time?
3. Most women also elect to make behavioral changes in their daily routine during pregnancy. What behaviors might a pregnant woman cease during her third trimester? What behaviors might she adopt during this time?

Self-Test

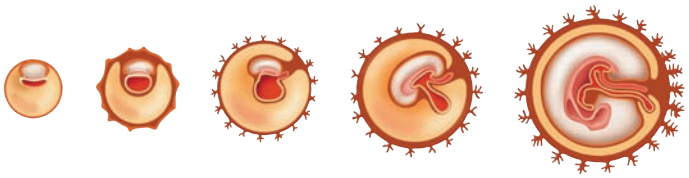
1. Capacitation includes all of the following EXCEPT _____.
   a. faster-moving flagella
   b. changes to the sperm head membrane
   c. acrosomal enzyme priming
   d. biochemical changes in the corona radiata

2. The very next step in fertilization following the one shown in this image will be _____.
   a. syngamy
   b. polyspermy
   c. implantation
   d. morula formation



3. The correct term for the settling of the blastocyst into the uterine lining is _____.
   a. capacitation
   b. implantation
   c. fertilization
   d. trophoblastation

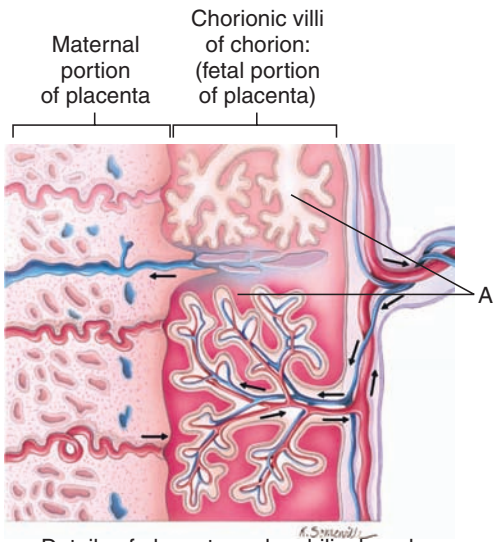
4. In the figure below, the cell layers destined to form the embryo are referred to as _____.
   a. ectoderm only
   b. mesoderm and endoderm
   c. endoderm only
   d. ectoderm, endoderm, and mesoderm



5. The extraembryonic membrane that develops into a protective fluid-producing membrane is the _____.
   a. amnion
   b. allantois
   c. yolk sac
   d. chorion

6. The extraembryonic membrane that develops into the placenta is the _____.
   a. amnion
   b. allantois
   c. yolk sac
   d. chorion

7. In the figure below, the structures labeled A are responsible for _____.
   a. producing amniotic fluid
   b. manufacturing fetal red blood cells
   c. digesting maternal endometrium
   d. producing hCG



Details of placenta and umbilical cord

8. After birth, the umbilical vein becomes the _____.
   a. foramen ovale
   b. hepatic portal system
   c. placenta
   d. round ligament

9. The sucking response develops in fetuses immediately prior to birth.
   a. True
   b. False

10. The trimester characterized by rapid changes, including the formation of blood cells, human facial features, and ovarian follicles, and development of the nervous and muscular systems to the point of "quickening," is the _____.
   a. first trimester
   b. second trimester
   c. third trimester
   d. fourth trimester

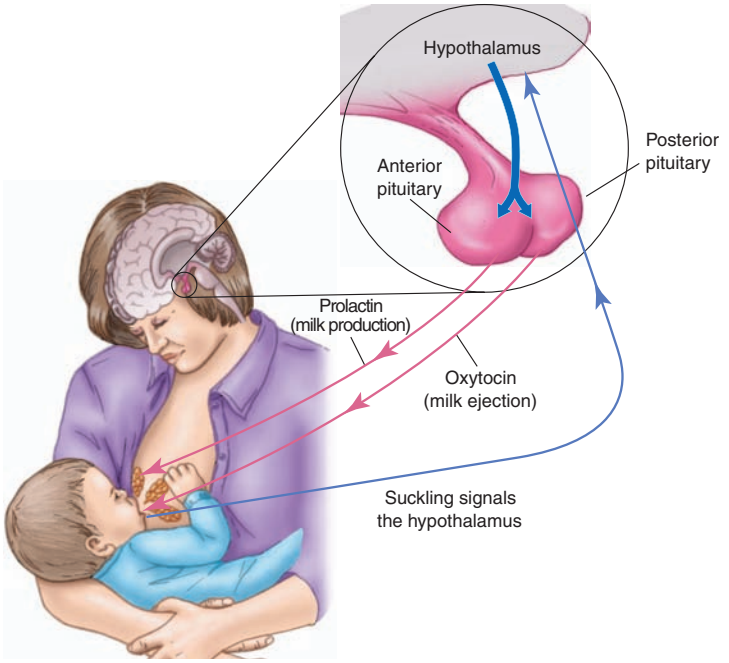
11. The type of feedback seen during labor is _____ feedback.
   a. positive
   b. negative
   c. hormonal
   d. unnatural

12. The hormone that initiates labor is _____.
   a. hGH
   b. hCG
   c. oxytocin
   d. ACTH

13. The correct order of the stages of delivery is _____.
   a. dilation → contraction → expulsion
   b. dilation → expulsion → afterbirth
   c. afterbirth → expulsion → dilation
   d. contraction → expulsion → dilation

14. The least invasive of the following means of assisting with labor and delivery is _____.
   a. cesarean section
   b. forceps delivery
   c. pitocin drips
   d. external manipulation

15. The hormone that produces milk as shown below is _____.
   a. hGH
   b. prolactin
   c. oxytocin
   d. Both hGH and prolactin are needed to produce milk.



THE PLANNER

Review your Chapter Planner on the chapter opener and check off your completed work.

Inheritance, Genetics, and Molecular Biology

We all enjoy learning the names of people on our family tree, even if we know very few of them personally. Each of us has an incredible number of ancestors to learn about: If you go back just seven generations, you have some 128 direct ancestors. If you go back 17 generations, to roughly the time when Christopher Columbus began exploring the Western Hemisphere, you have on the order of 131,072 direct ancestors (assuming no incest), each of whom contributed something to your genetic makeup. Even more amazing is the fact that all your direct female ancestors through countless generations had to experience well-timed hormone releases and successful pregnancies for the chain of descent to lead directly to you.

The exponential math works in the other direction as well: Some researchers have estimated that more than 35 million Americans are descendants of the 102 Caucasian Europeans who came over on the *Mayflower*. That's roughly 12% of the population, and they represent many different cultures and ethnicities.

Despite these incredible lineages, you have more in common with your immediate family than with your distant ancestors. Throughout life, an individual's genes are a key factor in his or her physical and intellectual prowess, susceptibility to disease, and even personality. How are these physical and mental traits inherited? How are gene-related problems inherited, and why do they appear in some children but not in others? To answer these questions, we turn next to genetics, inheritance, and DNA.

CHAPTER PLANNER

- ❑ Study the picture and read the opening story.
- ❑ Scan the Learning Objectives in each section:
  p. 556 ❑ p. 562 ❑ p. 566 ❑ p. 569 ❑ p. 575 ❑
- ❑ Read the text and study all figures and visuals. Answer any questions.

Analyze key features

- ❑ Process Diagram, p. 560 ❑ p. 561 ❑ p. 568 ❑
- ❑ What a Scientist Sees, p. 572
- ❑ I Wonder..., p. 574
- ❑ Biological InSight, p. 576
- ❑ Health, Wellness, and Disease, p. 581
- ❑ Ethics and Issues, p. 586
- ❑ Stop: Answer the Concept Checks before you go on:
  p. 562 ❑ p. 566 ❑ p. 569 ❑ p. 575 ❑ p. 587 ❑

End of chapter

- ❑ Review the Summary and Key Terms
- ❑ Answer the Critical and Creative Thinking Questions.
- ❑ Answer What is happening in this picture?
- ❑ Answer the Self-Test Questions.

CHAPTER OUTLINE

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- DNA Makes Up the Genes that Make Up the Chromosomes
- Gregor Mendel Explained Patterns of Inheritance
- Cell Division Is a Key to Genetics

Modern Genetics Uncovers a Molecular Picture 562

- Alleles Are Gene Variations
- Complete Dominance Is a Small Part of Our Phenotype
- Incomplete Dominance and Codominance Complicate the Picture
- Punnett Squares Show the Possibilities

The Central Dogma: Genes Direct the Formation of Proteins 566

- Transcription and Translation Convert DNA into Protein

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- Pedigree Charts Trace Traits Through Families
- Some Traits Are Sex-Linked
- Genetic Variations Are Usually Caused by Mutations
- Genetic Counseling Can Help Avoid Chromosomal Disorders
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Biotechnology Has Far-Reaching Effects 575

- Purified DNA Can Be Used in Laboratory Procedures
- Restriction Enzymes Are the "Scissors" of Biotechnology
- Transgenics and Clones Are Part of Our Brave New World
- Gene Therapy Can Correct Defects and Treat Disease
- DNA Technologies Can Be Used to Identify Individuals
- The Human Genome Project Mapped Human Genetics
- Genetics Helps Us Understand Evolution

20.1 Traits Are Inherited in Specific Patterns

LEARNING OBJECTIVES

1. **Explain** the origin of the 23 pairs of chromosomes in our body cells.
2. **Outline** Mendel's basic experimental plan.
3. **Describe** Mendel's two laws of inheritance.
4. **Describe** the difference between mitosis and meiosis.

What will my baby look like? Will it be intelligent? Short? Athletic? Oh my gosh, I hope it doesn't have my ridiculous ears or my horribly flat feet!" These common concerns reflect the fact that most of us are subtly aware that traits, appearances, and even intellect can be attributed to our **genes**. Genes, made of strings of DNA, contain the directions for making the millions of proteins that your body uses; we say that genes code for proteins. Genes and DNA are found in the nucleus of almost every cell in your body.

DNA Makes Up the Genes that Make Up the Chromosomes

If our genes are a way that DNA organizes itself, then our **chromosomes** are our genes' way of organizing themselves. Our chromosomes contain our genes, and our genes contain our DNA. It's a miraculous, multilevel information filing system, and more.

Only a few years ago, genetic researchers thought we must have over 100,000 different genes in our bodies, many more than a cat or mouse. We now know that isn't true. As of early 2008, the number of estimated genes in the human body is about 20,500. The problem for gene counters is that a long string of DNA (say, 300 nucleotides long) with a start and stop point looks like a gene, but it isn't one until we are sure it codes for proteins. If it doesn't have the instructions for making a protein, it isn't a gene. To complicate matters further, the same start and stop point may code for a few different proteins depending on how the intervening nucleotides are read.

We also now know that your genes are almost identical to the genes of any person next to you—more than 99% of our genetic material matches. Scientists refer to the exact sequence of nucleotides present on each individual's chromosomes as their **genotype**. We differ from each other in genotype by less than 1%, but that less than 1% makes all the difference in the world when discussing individuals.

Your DNA sequence codes for specific amino acids. DNA includes directions for making genes, so we say that DNA codes for them, as genes code for proteins. You may remember from Chapter 3 that DNA is composed of a four-base "alphabet," where three bases read as one "word." Your individual **DNA sequence** codes for the specific arrangement of amino acids in each of the millions of proteins in your body. The "genetic alphabet" of DNA may contain only four letters, but it is phenomenally sophisticated. The 3-billion-plus individual base pairs in the nucleus of the human cell spell out everything you need to become a human. Furthermore, this DNA exists in trillions of cells, and it can be copied thousands of times with little or no appreciable error. It's no wonder biologists are fond of saying that we have millions of miles of DNA in our bodies. Incredibly, the molecule is so durable that DNA found in fossils tens of thousands of years old can sometimes be analyzed! DNA is durable, but it is also easily lost in our shed cells, as more than one criminal has found.

DNA sequence The sequence of bases (adenine, cytosine, thymine, and guanine) on a chromosome.

Our chromosomes come in pairs. Genes are located on chromosomes. Humans have 23 pairs of chromosomes, for a total of 46 individual units of organized DNA. Twenty-three chromosomes came from the egg, and the matching 23 were delivered via the sperm during fertilization. This means the egg and sperm do not have the usual **diploid** chromosome complement (23 pairs). Instead, they are **haploid**, carrying only 23 individual chromosomes, one from each pair.

Genetic factors are important in determining our individuality. Chromosome 11, for example, carries the same basic information in all of us. It contains genes that

diploid Having the total number of chromosomes of the body cells, twice that of the gametes.

haploid Having half the number of chromosomes of normal body cells, found in eggs and sperm.

code for some blood proteins, insulin, and the metabolic enzyme lactate dehydrogenase, as well as other proteins and regulating factors. The specifics of the information on your chromosome 11, however, are different from those found on the same chromosome in either of your parents. Think of building a planned neighborhood. Each house could have the same general blueprint and floor plan, but still look a bit different. Maybe the front doors are all centered, but with different arrangements of windows. On first glance, the neighborhood might look diverse, but with some study, you would notice important similarities among the houses. The same could be said about human beings. Hair can change. Facial proportions and muscular development can change. Deep within the cells, however, we are almost exactly the same.

Gregor Mendel Explained Patterns of Inheritance

Natural patterns seen in the inheritance of traits or characteristics were manipulated long before genes and chromosomes were discovered. For thousands of years, herders and breeders of animals have known they could develop better animals through selective breeding. Dog breeding, for example, is one of the oldest uses of genetics. Humans interbred those dogs with the traits they liked and could use: Some became hunting dogs (labs or pointers), some became sled dogs (huskies) or herders (border collies), and so on. Selective breeding also happened in the plant kingdom. Farming apparently developed as early farmers learned they could improve on food crops by wise choice of the parent plants.

Farmers and herders brought wild plants and animals into domestication and greatly improved their yields, but they had no scientific understanding of the mechanisms of the improvement. Only in the 19th century did a monk from Central Europe provide a plausible—and accurate—theory. His discoveries, along with those of Charles Darwin, gave rise to most of our understanding of modern biology.

Gregor Mendel was not only a monk—he was also a scientist able to use observation, experimentation, and the scientific method to help explain what he saw. He devoted years to studying the inheritance of traits in many plants, including garden peas.

The garden pea is an easy-to-grow plant with specific and definable traits, and it produces a simple flower. Left alone, pea plants will produce mature pollen (the male gamete), which falls on the female reproductive parts of the plant—the stigma within the flower. Pollen tubes grow through the female stigma into the ovary. Once this pollen contacts the eggs, fertilization occurs and seeds develop.

Mendel realized he could control this process, and in doing so could gain an understanding of the processes of inheritance. He started by identifying traits in the pea plant that existed in only two forms and did not blend. For example, he noticed that pea flowers were purple or white, but never lavender, and the seeds were either yellow or green. In total, Mendel identified and studied seven nonblending traits: flower color, seed color, seed shape, pod color, pod shape, flower and pod position, and plant height, as shown in Table 20.1.

The seven traits Mendel used to study genetic inheritance Table 20.1

TRAIT	DOMINANT	×	RECESSIVE
Flower color	 Purple	×	 White
Seed color	 Yellow	×	 Green
Seed shape	 Round	×	 Wrinkled
Pod color	 Green	×	 Yellow
Pod shape	 Round	×	 Constricted
Flower and pod position	 Axial (along stem)	×	 Terminal (at top of stem)
Plant height	 Tall	×	 Dwarf

self-pollinating
Transferring the pollen of a flower directly to the stigma of the same flower.

cross-pollinating
Fertilizing the ovum of a flower with pollen from a different plant.

Using these traits, Mendel began his unparalleled experiments, **self-pollinating** and **cross-pollinating** his plants, then recording how the individual trait he was studying appeared in the offspring. In each test, Mendel observed hundreds of plants. As he followed these traits, he observed some surprising results—results that to this day accurately predict the outcome of genetic crosses. Figure 20.1 shows an example of Mendel's experimental methods, breeding a purple plant with a white one.

Heritable units exist and randomly separate during gamete formation. Mendel discovered that not only are traits inherited but also the proportion of each trait in the next generation is fixed. If he began by crossing **true-breeding** parents displaying opposing traits (true-breeding plants produce the same traits in their descendants with every self-pollination), all the offspring in the first generation had only one of the parental traits. In experiments such as this, the first generation is referred to as the F_1 generation, short for first filial generation. For example, in crossing a purple-flowered plant with a white-flowered plant, the F_1 generation was 100% purple. It appeared that purple was **dominant** over white.

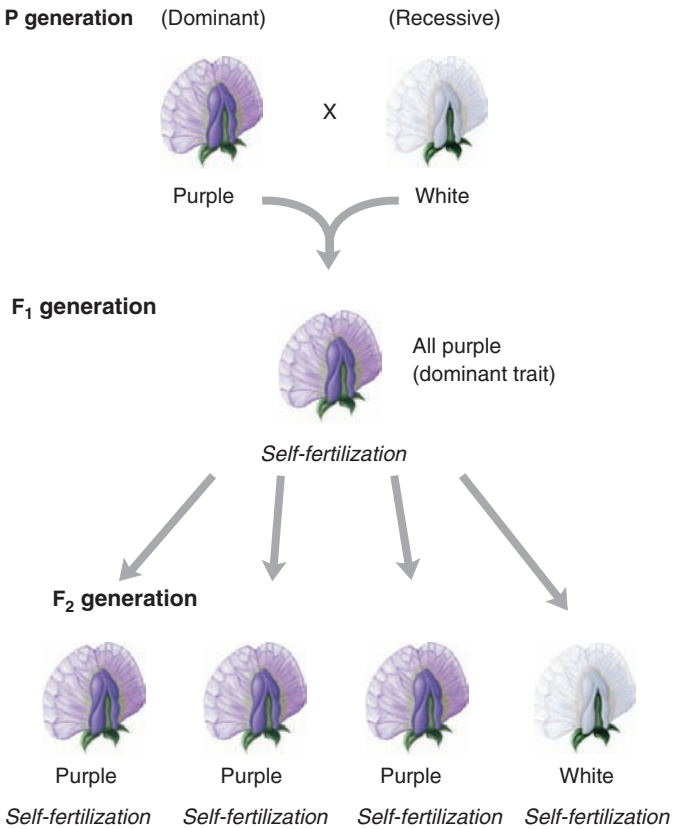
What had happened to the **recessive** (nondominant) white color? When Mendel self-pollinated the F_1 plants, the white flowers miraculously reappeared in the second generation, F_2. Oddly, flower color always had the same ratio: roughly one white-flowered plant for every three purple-flowered plants.

In seeking an explanation, Mendel decided there must be some "heritable unit," which we now understand as the various forms of genes. The term "genes" wasn't coined until 1913, well after Mendel died. Mendel hypothesized that these "heritable units" must exist in pairs in the parent and that these pairs separate as pollen and egg are formed. Each gamete would carry only one of the parent's "heritable units." Therefore, one of these "heritable units" from each parental plant is transferred to each offspring. Mendel called this the **law of segregation** and defined it as the random separation of parental "heritable units" during gamete formation. We now know this random separation is possible because of the special type of cell division called meiosis, which we will return to.

Mendel also formulated the law of independent assortment. As Mendel's experiments got more sophisticated, he tracked several traits at once through dihybrid crosses (following the fate of two traits rather than just one), and again he saw a pattern. Mendel noticed that when a plant dominant for two traits is cross-pollinated with a plant recessive for both traits, the second, self-fertilized generation (F_2) will show a predictable 9:3:3:1 ratio of dominant and recessive traits. There seemed to be no connection between the expression of one trait and the expression of the other. The expression of each trait was independent from the expression of any other. In other words, even if a pea plant's flower color was dominant, he could not predict whether its seed color

Mendel's experiment for one trait • Figure 20.1

In the first generation, Mendel cross-pollinated two true breeding parents demonstrating opposite traits. In this example, he bred a purple flowered plant with a white flowered plant. He then recorded the flower colors of the first generation from this cross. He permitted the first generation to self-pollinate, and again recorded the results for every plant in the second generation.



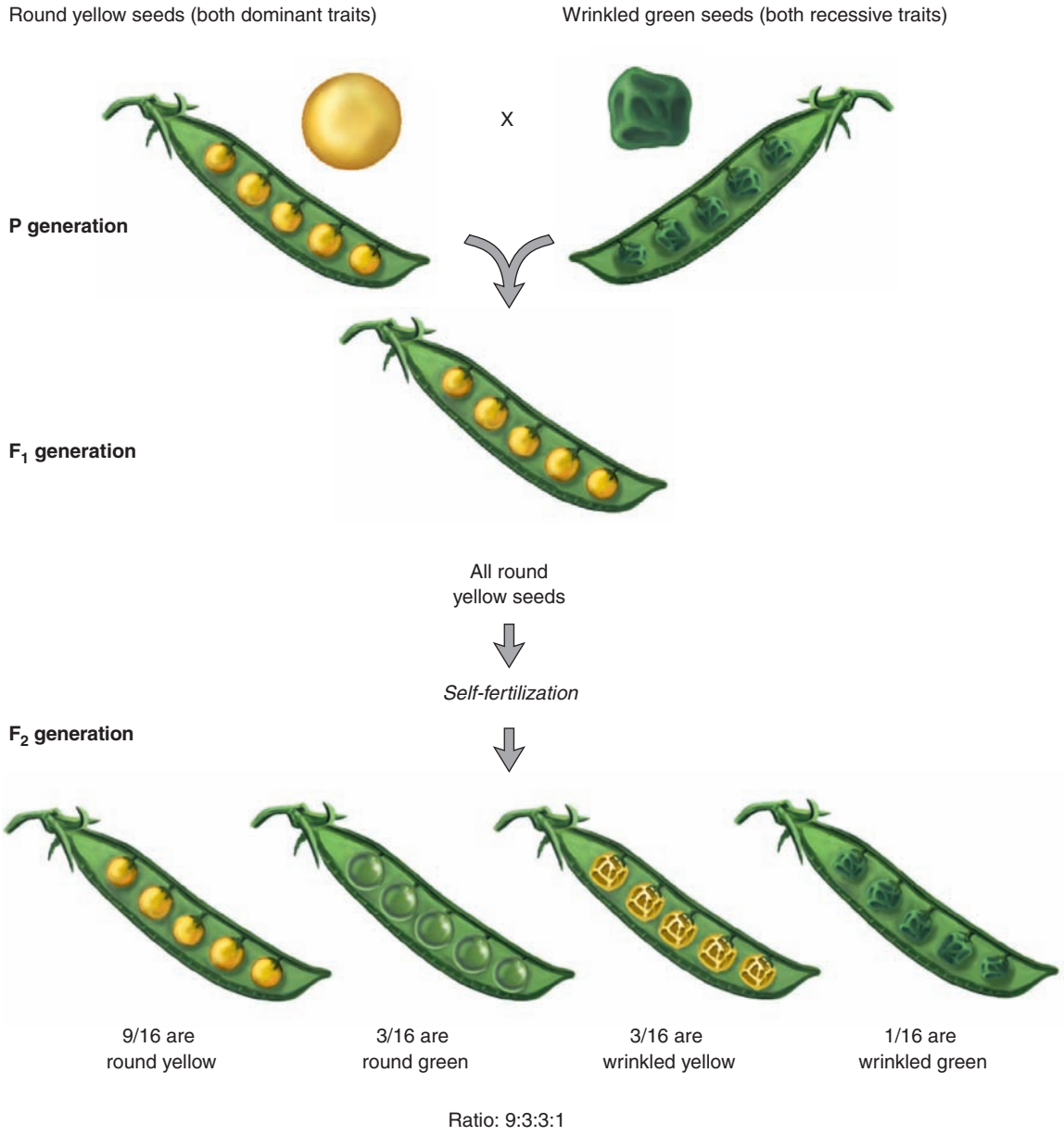
would also be dominant. Mendel's **law of independent assortment** states that each trait is carried in the egg and pollen as a separate entity, with no effect on any other trait. We now know that things are a bit more complicated than Mendel's law of independent assortment states, but he was on the right track. These crosses are depicted in Figure 20.2.

Cell Division Is a Key to Genetics

Mendel's extraordinary experiments and insights brought us the terms "dominant" and "recessive." However, Mendel didn't know about the existence of genes or chromosomes or the details of cell division. Our current understanding of the details of cell division has helped explain Mendel's early work in genetics.

Mendel's pea experiment for two traits • Figure 20.2

Mendel's second set of experiments traced the fate of two traits at once, resulting in a 9:3:3:1 ratio of dominant and recessive traits in the F_2 generation. The experiments led directly to his law of independent assortment.

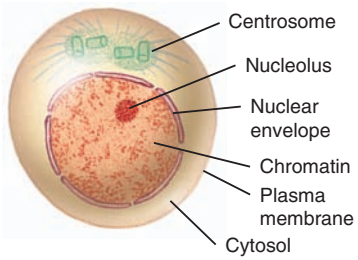


PROCESS DIAGRAM

Mitosis • Figure 20.3

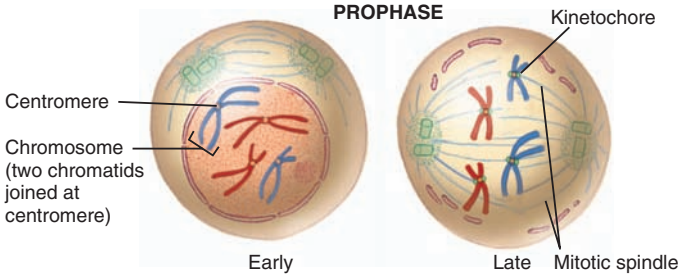
THE PLANNER

INTERPHASE



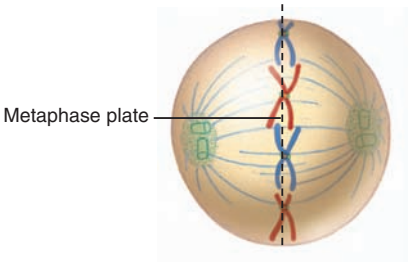
1 **Interphase** is the "resting" phase. The cell is not dividing, but rather carrying out its normal duties. The nuclear membrane is intact, the DNA is loose and unwound in chromatin threads, and nucleoli are present. In a cell that is destined to divide (some, like skeletal muscle and nerve cells, do not divide), the DNA and centrioles double during interphase, but interphase is not considered part of mitosis.

PROPHASE



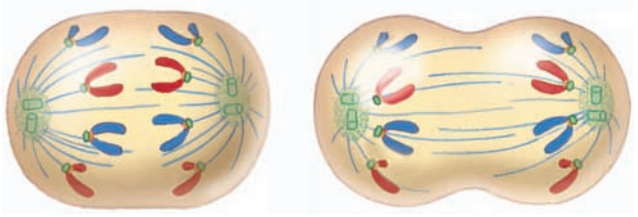
2 In **prophase**, the nuclear membrane disappears; the chromatin condenses and becomes visible in the cell as chromosomes; the centrioles separate and migrate to opposite ends of the cell. As the centrioles migrate, the spindle apparatus is formed. This is a network of microtubules that attach to the middle of each chromosome. Prophase is the longest phase of mitosis.

METAPHASE



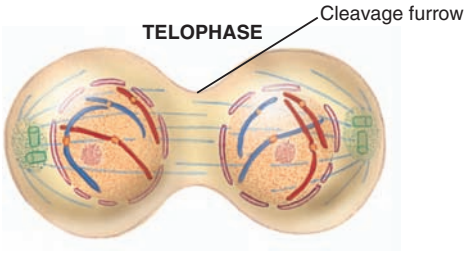
3 In **metaphase**, the middle phase of mitosis, the chromosomes are lined up on the central axis of the cell. As soon as the chromosomes are aligned, anaphase begins.

ANAPHASE



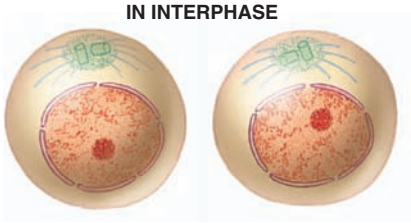
4 In **anaphase**, the spindle apparatus shortens, pulling the two arms of the chromosome in opposite directions. As the spindle fibers shorten, the chromosome separates at the middle, and the two arms are pulled away from each other. Anaphase is very quick, but it is here that the doubled genetic material separates into the exact amount of DNA needed for each daughter cell.

TELOPHASE



5 **Telophase** is the final phase of mitosis. The chromosomes, now separated into two equal groups, de-condense into chromatin, and the DNA returns to its original thread-like appearance. Nuclear envelopes form around these chromatin groups. The center of the cell pinches to form a cleavage furrow. The furrow deepens, eventually separating the cell into two separate cells, each with a nucleus containing the same amount of DNA as the parent cell.

IDENTICAL CELLS IN INTERPHASE



6 The two daughter cells contain identical genetic material, and are clones of the single parent cell. Once division is completed, the daughter cells are in interphase, meaning they have begun a new growth phase. Eventually they will each reach the size of the original cell. They may undergo mitosis as well, individually moving through the cycle again.

WILEY PLUS Interactivity

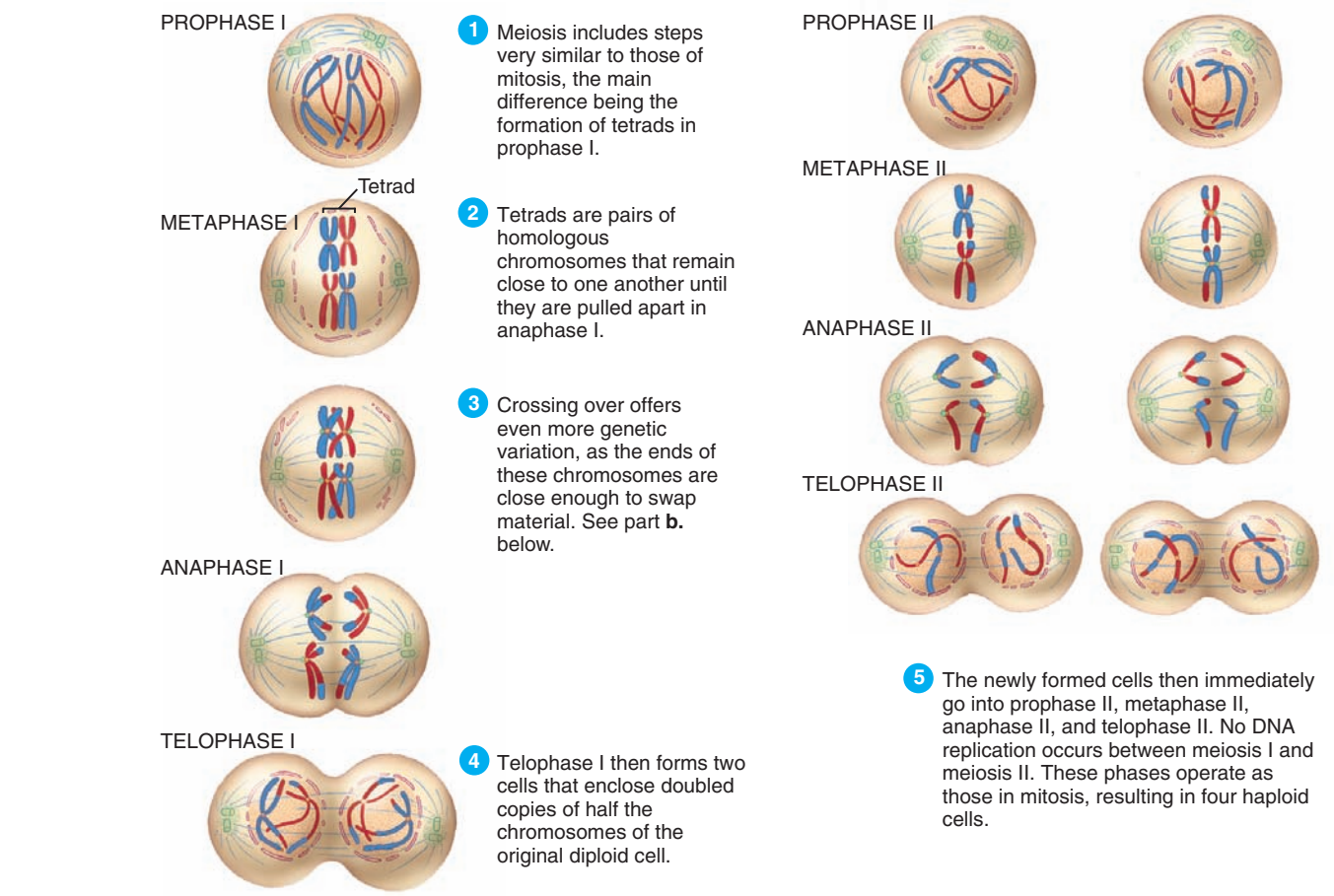
The most well-coordinated, communication-rich event in a cell's life cycle is one kind of cell division called **mitosis**. Mitosis occurs constantly in the human body, with some cells dividing to form two daughter cells as often as every seven days. To carry out this complicated process, the cell must communicate with surrounding cells as well as its own organelles and biochemical pathways. During mitosis, DNA and organelles must be duplicated, and the DNA must then be condensed into manageable packets and sorted into separate nuclei. Once the DNA is separated into two nucleii, the original cell is divided and two separate, intact cells are formed, each containing all of the organelles and DNA of the parent cell. The stages of nuclear division, or mitosis, are described in Figure 20.3.

Meiosis is the second kind of cell division. Meiosis is a second kind of cell division, but one that happens only in sex cells. Passing on your genes requires you to form haploid gametes. As we have seen, gamete is a general term for the reproductive cells that will form a new individual, in our case the egg and sperm. These are produced via meiosis, a specialized type of cell division that ensures the equal and orderly division of chromosomes. This process is shown in Figure 20.4. In order to form gametes properly, the normally **diploid** chromosome number must be cut in half, with the resulting gametes having exactly half the usual complement. This way, when two **haploid** gametes unite to form a **zygote**, the original diploid number is restored. The division must be accomplished

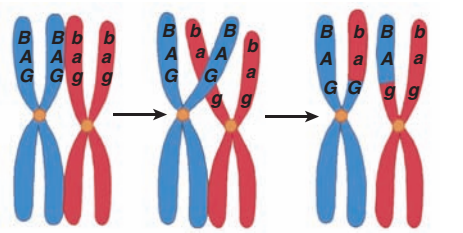
PROCESS DIAGRAM

Meiosis • Figure 20.4

THE PLANNER



a. Stages of meiosis



b. Details of crossing-over during prophase I

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Meiosis is the orderly distribution of genetic material to newly formed haploid gametes. It includes steps very similar to those of mitosis, the main difference being the formation of tetrads in prophase I. Crossing over at this stage offers even more genetic variation, as the ends of these chromosomes are close enough to exchange genetic material. Telophase I then forms two "cells" that immediately go into prophase II, metaphase II, anaphase II, and telophase II. These phases result in four haploid cells.

so that each gamete has a predictable and reliable half of the chromosomes. Rather than being randomly split, **homologous** chromosomes come together and are then separated, one to each new gamete.

homologous Similar in structure, function, or sequence of genetic information.

In the male, meiosis occurs exactly as depicted in Figure 20.3, and four sperm are produced from two divisions of a primary **spermatocyte**. Females produce only one egg from each round of meiosis, investing almost all of the cytoplasm and organelles in one gamete. The extra genetic material that is split out at anaphase I and anaphase II is ejected from the developing egg with very little associated cytoplasm. Regardless of whether an egg or four sperm are being produced, meiosis I separates homologous chromosomes by breaking apart tetrads, whereas meiosis II produces haploid gametes.

CONCEPT CHECK STOP

1. **How** many chromosomes are carried in the egg? In the sperm?
2. **What** was Mendel's basic experimental plan?
3. **How** does Mendel's law of segregation differ from his law of independent assortment?
4. **What** is the main difference between mitosis and meiosis?

20.2 Modern Genetics Uncovers a Molecular Picture

LEARNING OBJECTIVES

1. **Explain** the interaction of dominant and recessive alleles.
2. **Describe** how alleles can also be multifactorial or codominant.
3. **Analyze** a Punnett square.

Mendel's experiments provided a great starting point for the science of genetics, although their significance was not recognized for almost 40 years. To understand inheritance as we now know it, we need more terms than "dominant" and "recessive." Let's run through some of those terms.

We all have the same basic arrangement of genes in our chromosomes, despite individual differences in **phenotype**. Your phenotype is all your observable traits or characteristics, including ones that are not easily seen, like blood type or color blindness. These phenotypic differences emerge from subtle differences in **genotype**—our complete set of genes—as well as environmental factors. Our phenotype is the result of our genotype and all the environmental influences on us, including the quality of our food, the type of shelter we live in, and even our financial "health."

phenotype An organism's observable characteristics as a result of the genes and alleles being expressed.

genotype The genes and alleles carried on the chromosomes.

Alleles Are Gene Variations

Genes are found in specific locations on their chromosomes. We know that chromosomes come in pairs, which means genes come in pairs as well. Each member of the gene pair is called an **allele**, and the members can be identical to each other or slightly different. An allele is an alternative form of a gene. It is the differences in alleles that give rise to different genotypes.

Alleles may have differences in the sequences of only one or a few DNA base pairs, but that small difference means they produce different proteins than their counterpart genes. That less-than-1% genotype difference

between you and your neighbor or roommate is because of slightly different alleles, which combine to give rise to some very different phenotypes.

somatic Related to the body, in contrast to the gametes.

We have seen that each **somatic** cell contains two copies of every gene, one obtained from each parent. When the two alleles are identical, the genotype is **homozygous** for the trait that is controlled by those alleles. A homozygous gene is usually denoted by two identical letters, such as AA or aa. The capital **A** indicates dominance for that trait, and the small **a** indicates recessiveness. Homozygous individuals can be **homozygous dominant**, meaning both alleles code for the dominant trait (AA), or **homozygous recessive** (aa). If one allele codes for the dominant trait and the other codes for a recessive trait, the genotype is **heterozygous**. Heterozygotes are usually indicated with a capital and a lowercase letter (Aa).

We can see that sexual reproduction creates new mixtures of genes and alleles for each generation. The randomly created mixture that helps our survival and reproduction tends to get passed on and spread to others.

Complete Dominance Is a Small Part of Our Phenotype

Only homozygous recessive individuals express a recessive phenotype. If one allele is dominant, the dominant phenotype must be expressed. This means that if your appearance includes a recessive trait, all of your gametes carry only the recessive allele. You are homozygous recessive for that trait. If that trait is dominant in your phenotype, you could be homozygous dominant or heterozygous, and it is hard to predict which allele any one of your gametes will carry.

We all have traits that define our phenotype: hair that is brown, black, blonde, or red; eyes that are blue, green, brown, or hazel; hair that is straight or curly; skin that is dark or light. As it turns out, however, human inheritance is more complicated than that of Mendel's pea plants. Some of our phenotypic traits come from one allele completely dominating another, as in Mendel's plants. However, most alleles do not follow the simple dominance pattern, as we will see. In fact, only a few of our phenotypic traits demonstrate simple dominant–recessive interactions. These traits are listed in Table 20.2.

Dominant/recessive traits in humans **Table 20.2**

Trait	Dominant phenotype	Recessive phenotype
Cleft in chin	No cleft	Cleft present
Hairline	Widow's peak	Straight hairline
Eyebrow size	Broad	Slender
Eyebrow shape	Separated	Joined
Eyelash length	Long	Short
Dimples	Dimples	No dimples
Earlobes	Free lobe	Attached
Eye shape	Almond	Round
Freckles	Freckles	No freckles
Tongue rolling	Roller	Nonroller
Finger middigital hair	Hair	No hair
Hitchhiker's thumb	Straight thumb	Hitchhiker's thumb
Interlaced fingers	Left thumb over right	Right over left
Hair on back of hand	Hair	No hair

We can predict the possibility of passing these traits on to our offspring just as Mendel did with his peas. The alleles exhibit **complete dominance**. Although these traits are not critical to our overall **fitness**, they do demonstrate that a few human genes follow the same rules as Mendel's pea plants.

fitness Ability to produce living offspring and pass on DNA.

Incomplete Dominance and Codominance Complicate the Picture

Many traits in humans, including hair color, eye color, and facial structure, exhibit **incomplete dominance** or **codominance** rather than the complete dominance that Mendel found. That is, the traits result not from one gene dominating another but from several genes affecting the phenotype simultaneously. How can this happen?

Incomplete dominance tends to produce different phenotypes based on the combination of alleles present in heterozygotes. The trait produced is an intermediate one: Instead of straight or curly hair, incomplete dominance leads to something in the middle—wavy hair.

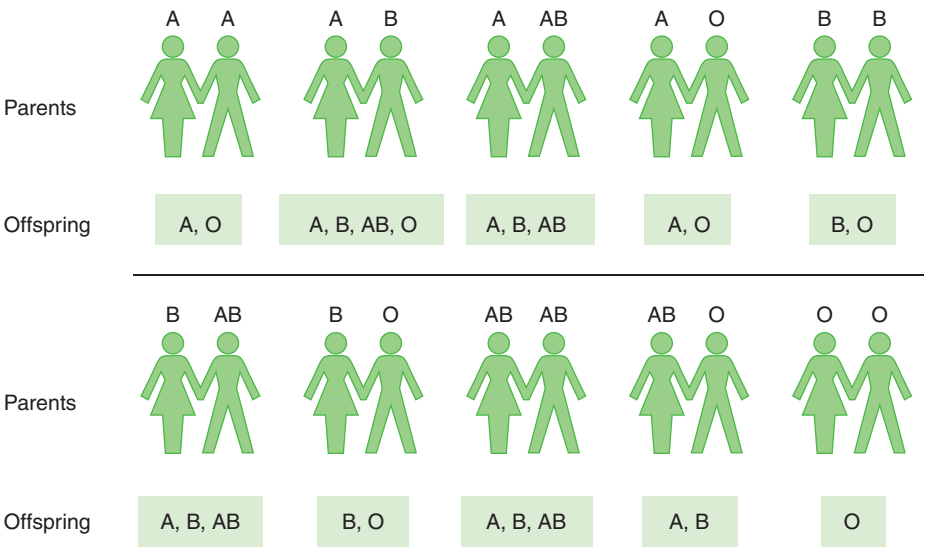
Codominance occurs when the effect of both alleles appears in the heterozygote. We will see that blood types are good examples of codominance.

Many human traits are also **polygenic**, meaning the phenotype results from the interaction of many genes, not the expression of just one. Furthermore, many of our traits are **multifactorial traits**, meaning polygenic traits that are also influenced by environment. These traits express a continuum of phenotypes, usually producing a bell-shaped curve on a plot of their distribution in the population. Body type, muscular development, fat deposition, and height are all multifactorial traits.

Blood type is an example of codominance. Blood type is an excellent example of codominance, as seen in Figure 20.5. There are three alleles for blood type: the A allele, the B allele, and the O allele. The A allele codes for a modification of the original precursor erythrocyte surface protein randomly designated "A." Similarly, the B allele codes for modifications that produce the marker protein B. The O allele codes for no modified marker protein, effectively a null allele. If one of your alleles is A and the other is A or O, you have type A blood. Similarly, if you have two B alleles or a B and an O, your blood type is B. If one allele is A and the other B, however, you have type AB blood. If you are homozygous O, you have type O blood. In each case, both alleles are expressed in the phenotype, which is the meaning of codominant. The alleles do not blend to form an entirely new AO marker protein, nor do they form an AB protein that is different from the individual A or B modified markers. Instead, each allele codes for a separate protein, which is translated and added to the membrane of the red blood cells. Therefore, in type AB blood, the erythrocytes show both the A and the B protein, and with the genotype AO you will find both an A and an O marker on the red blood cells.

Incomplete dominance governs the human voice pitch, eye color, and hair curliness. The lowest and highest pitches in male voices occur in men who are homozygous dominant (AA) or homozygous recessive (aa) for the trait that determines pitch. All intermediate-range (baritone) voices are heterozygous (Aa). We see the same blending of traits in eye color. If one parent has green eyes and the other has brown, there is a good chance the children will express a blended, dark blue eye color. Recently, scientists have discovered that eye color is determined via an interaction of at least three different genes, each affecting the phenotype of the other. Although this trait requires more than one gene, the interactions between them can be understood in light of incomplete dominance. In Caucasians, hair can be straight (H'H'),

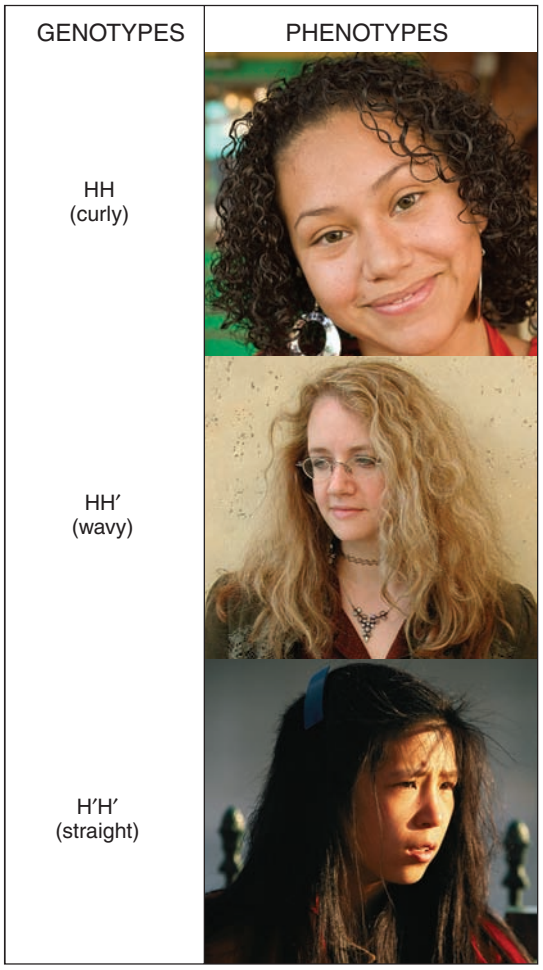
Blood type inheritance • Figure 20.5



There are three different alleles for human blood type: A, B, and O. Each of us has two blood type alleles, one from our biological mother and one from our biological father. We all have one of the following allele combinations: AA, AO, AB, BB, BO, or OO. For an AA or AO combination, the blood type is group A. For BB and BO, the blood type is B. For OO, the blood type is O. The figure shows ten sets of parents with various blood types and their offspring's possible blood types.

Hair patterns • Figure 20.6

Note that the uppercase and lowercase conventions are not used here because one trait is not dominant over the other.



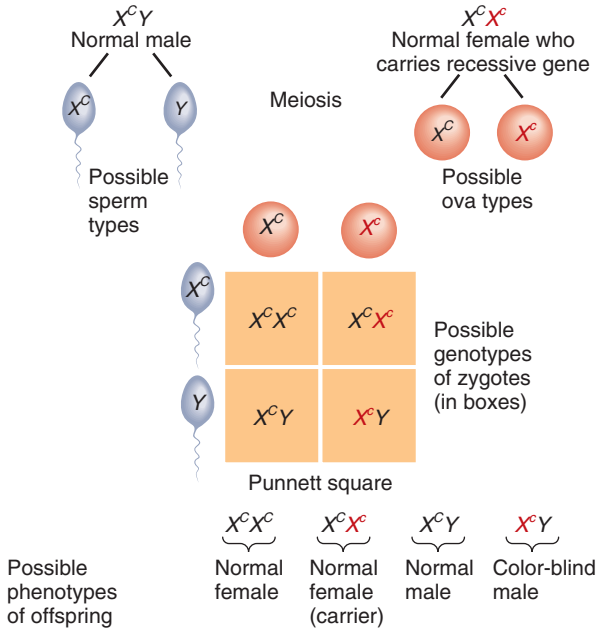
wavy (HH'), or curly (HH). Wavy hair is an intermediate phenotype, indicating incomplete dominance of the curly trait, as seen in **Figure 20.6**.

Punnett Squares Show the Possibilities

The Punnett square, a tool used to determine the probability of genotypic combinations in offspring, works much like the multiplication tables you may remember from grade school. The alleles carried by one parent for the gene in question are listed across the top, representing that parent's potential gametes. The left side lists the other parent's alleles. In the center boxes of the table, the allele at the top and the one to the left are "multiplied" or combined, resulting in one possible allelic combination from these two parents.

Sex chromosomes carry different traits, and Punnett squares help us figure them out. Further complicating the inheritance pattern of humans, the sex chromosomes (X and Y) carry different traits. There are more alleles on the X chromosome than on the Y, meaning that there are not matching alleles on these two chromosomes. Males (XY) have only one copy of the alleles found only on the X chromosome. The gene that codes for color vision is one such allele. The gene for color discrimination is on the X chromosome but not the Y. If a female XX carries the gene for color blindness on only one of her two X chromosomes, she will not express the defect, but half of her eggs will carry the defective gene. However, her sons are in danger of being color-blind. Because the fertilizing sperm carries a Y chromosome, it cannot provide a second copy of that allele to overcome the defect with a correct copy of the gene, resulting in a color-blind male child. Despite these differences, inheritance patterns for these so-called sex-linked traits, which we will cover later in this chapter, can be predicted using a simple Punnett square (named after a fascinating British biologist who wrote one of the first texts on genetics). See **Figure 20.7** for an example of a Punnett square.

Punnett square for the inheritance of red-green color blindness • Figure 20.7



Punnett squares predict phenotypic ratios. Punnett squares predict the phenotypic ratios that Mendel observed in his pea plant experiments. Crossing a homozygous dominant individual and a homozygous recessive individual yields 100% heterozygous offspring, regardless of the trait. All of the offspring will express the dominant trait. Self-pollinating these heterozygotes yields three phenotypically dominant offspring and one phenotypically recessive individual (who has a homozygous recessive genotype). The same Punnett square can be used to represent flower color in peas or attached earlobes in humans. It is amazing that Mendel accurately explained this using his "heritable unit" theory without any knowledge of genes or chromosomes. Even with inheritance patterns of codominance or incomplete dominance, Punnett squares predict the proportions of potential genotypes of the offspring. The phenotypic expression of those genes may not yield the typical 3:1 or 9:3:3:1 ratios expected by Mendel, but the genotype ratios remain the same.

CONCEPT CHECK STOP

1. **How** do dominant and recessive alleles interact?
2. **What** are multifactorial traits? Codominant traits?
3. **What** can be learned from a Punnett square?

20.3 The Central Dogma: Genes Direct the Formation of Proteins

LEARNING OBJECTIVES

1. **Summarize** the steps in transcription and translation.

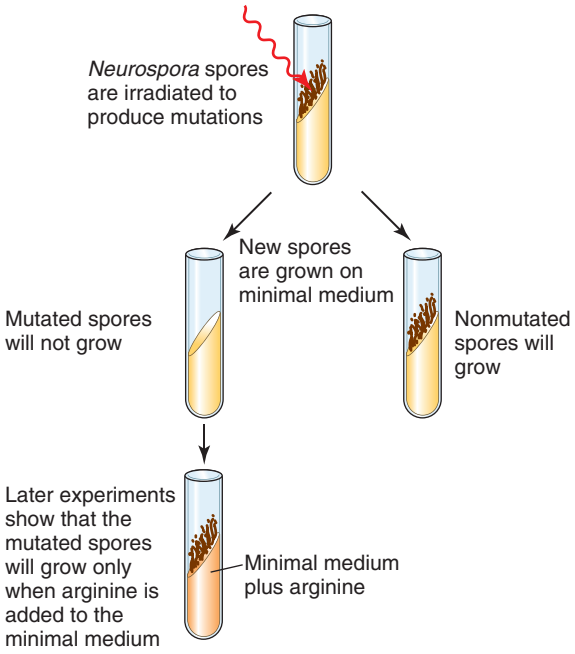
How do we know that alleles are the heritable units of Mendel's observations? Although this seems obvious now, considerable time and several breakthroughs were required to identify the "heritable unit" and then to find out where it existed in the cell and to determine how it worked. In 1941, two scientists demonstrated that DNA was the chemical in Mendel's "heritable unit." George Beadle and Edward Tatum, using cultures of the fungus *Neurospora*, showed that one sequence of DNA coded for one protein. This **one gene codes for one enzyme** idea marked the beginning of our understanding of how DNA produces proteins. Before this, it was thought that proteins might contain the unit of heredity because they occur in such enormous variety. Early scientists thought that since 20 amino acids make up the myriad proteins in the body, but only four nucleotides comprise DNA, surely the amino acids were the key to inheritance. This line of thought suggested that proteins were the basis of heredity.

Although proteins seemed a logical candidate as the genetic material, many scientists had begun to question this theory. Beadle and Tatum began looking for a way to conclusively identify the heritable unit. They understood that X-rays caused inheritable mutations that could prevent proper functioning of some pathways in organisms. They reasoned that if they could "knock out" and then restore a function, they could learn what molecule was carrying the information that the radiation destroyed. Beadle and Tatum demonstrated that knocking out one gene inhibits the function of one protein. This was good evidence that DNA controls protein production. Their experiment is summarized in Figure 20.8.

Transcription and Translation Convert DNA into Protein

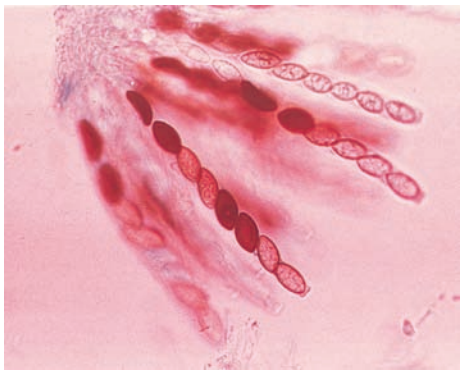
The next step was to determine how DNA controls the production of proteins. This mechanism has two steps: **transcription** and **translation**. These paired processes convert the information carried on DNA into proteins for the cell. Transcription is copying information from one

The one gene, one protein theory • Figure 20.8



a. Experiment by Beadle and Tatum

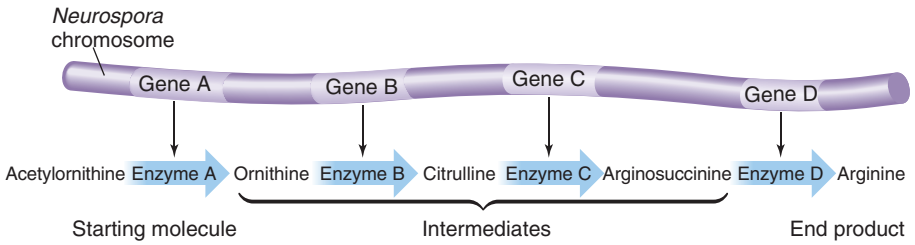
Beadle and Tatum used *Neurospora* mold because its meiotic products could easily be inspected. The researchers caused mutations in single genes and recorded the results. By adding or taking away sugars and other compounds from the media, they found which enzymes and metabolic reactions of the mutants were absent. Their observations showed that one gene controlled one enzyme in a metabolic reaction.



b. *Neurospora crassa*

Genes direct the synthesis of specific enzymes, which catalyze reactions in biochemical pathways.

Further experiments can show that the mutation is in one of the genes that codes for one specific enzyme required for the production of arginine.



c. Synthesis of the amino acid arginine

medium to another using the same language or alphabet. As you hear a lecture and take notes, you transcribe the information you hear into written form. Translation is converting information from one language to another. If English is not your native tongue, you may be translating the words on the page into a more familiar language as you read them. In the formation of proteins, the meanings of transcription and translation are similar.

Transcription is a change in medium. The information for new proteins is encoded in DNA that is stored in your cell nuclei, but the machinery for making proteins resides in the cytoplasm. Transcription is the copying of a sequence of nucleotide bases in DNA to **messenger RNA (mRNA).** Unlike DNA, mRNA can leave the nucleus and carry information from the DNA to the cell's protein-producing machinery.

As discussed in Chapter 3, there are structural differences between DNA and RNA. RNA is a single-stranded molecule, composed of individual nitrogenous bases arranged along a sugar phosphate backbone. Although this backbone is similar to that in DNA, the sugar in RNA is ribose, not the deoxyribose of DNA. The nitrogenous base thymine found in DNA is replaced by **uracil** during RNA synthesis. The usual base-pairing rule of DNA (A to T and C to G) is altered in RNA because of this substitution. Here the bases pair up A to U and C to G.

Translation makes the proteins. After the DNA code is transcribed to mRNA, it must be converted (translated) from nucleic acid "language" to amino acid "language." This occurs at the ribosomes, using **transfer RNA (tRNA)** to match up amino acids with mRNA bases.

Transcription and translation • Figure 20.9

THE PLANNER

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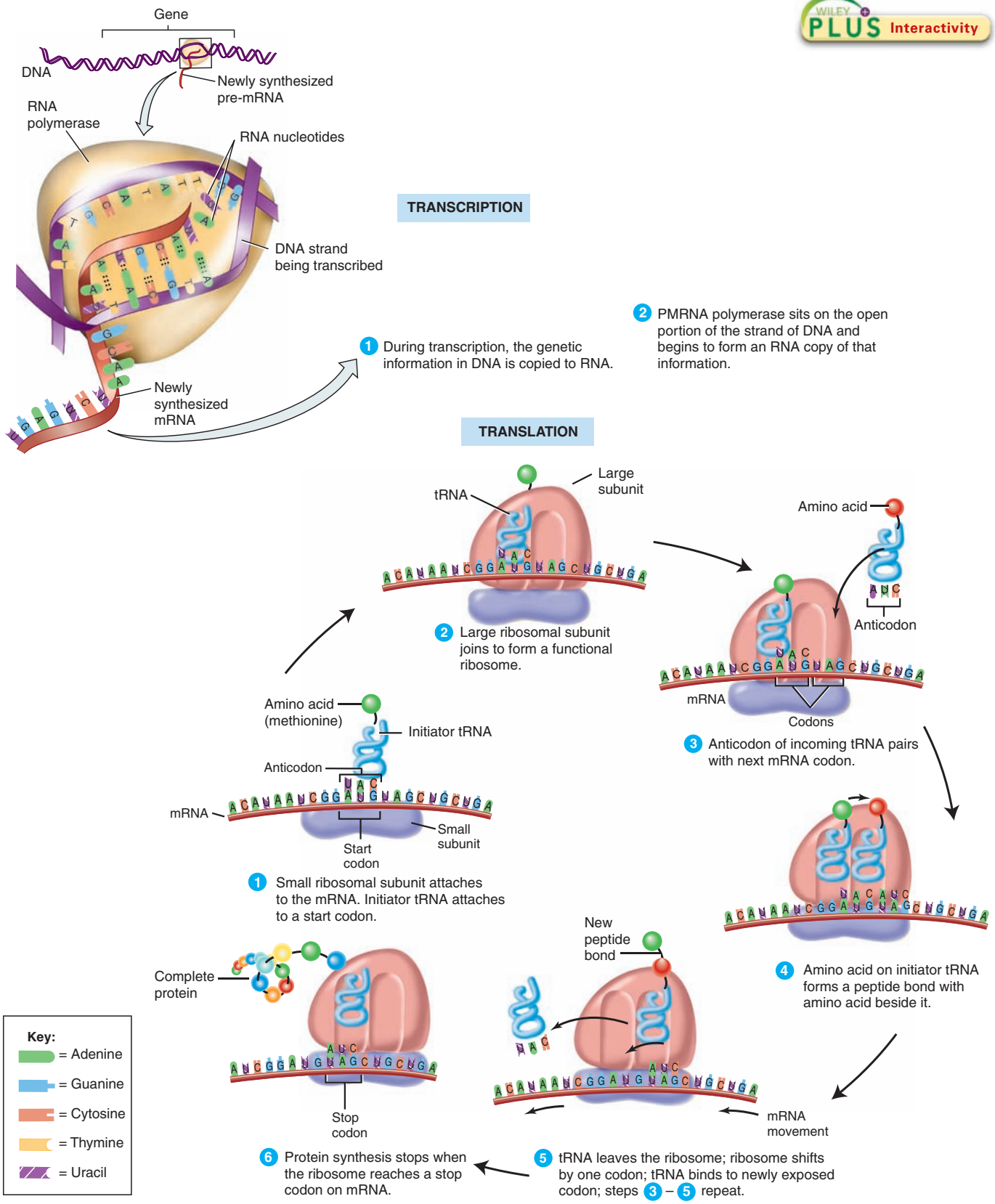


Messenger RNA is "decoded" by tRNA three bases at a time. These three bases on mRNA are called a **codon**. The matching three bases on the tRNA molecule are the **anticodon**. When codon and anticodon meet at the ribosome, the amino acid carried by the tRNA is incorporated into the growing polypeptide chain. Each codon indicates 1 of the 20 amino acids.

Biologists call the mechanism of transcription and translation the "central dogma of biology" because it has relevance to all aspects of their science. We now know that the "central dogma" is not quite "one gene, one protein." In some cases, one gene makes just a part of a protein rather than a whole protein. Figure 20.9 outlines these important biological processes.

CONCEPT CHECK STOP

1. **What** are the steps of transcription? The steps of translation?

20.4 Genetic Theory Is Put to Practical Use

LEARNING OBJECTIVES

1. **Explain** the information in a pedigree chart.
2. **Define** sex-linked traits.
3. **Describe** chromosomal disorders and genetic counseling.
4. **Compare** the values and costs associated with prenatal testing.

Couples often request genetic counseling before they choose to conceive. Genetic counseling is the practice of predicting the potential combinations of alleles two individuals may produce. If there is a family history of congenital disease, or if the potential parents feel they are at risk of carrying a detrimental recessive allele, genetic counseling can help alleviate their fears. Knowing the probability of having a child with a genetic anomaly can help couples decide whether to conceive.

Pedigree Charts Trace Traits Through Families

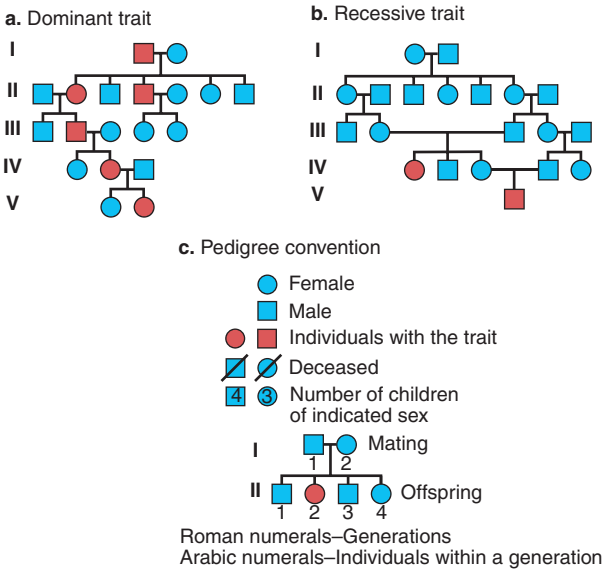
Pedigree charts are symbolic representations of genetic transmission of phenotypic traits through families. Using a pedigree chart like the one shown in Figure 20.10, researchers can trace the pathway of a disease through families, and characteristics of its transmission can be deduced. If, for example, the disease is **autosomal** dominant, anyone with alleles Aa or AA will be afflicted. If the disease shows up sporadically or appears in a child of two **asymptomatic** parents, the disease is probably autosomal recessive, and both parents are heterozygous carriers for the dysfunctional allele.

autosomal Any chromosome other than the sex chromosomes, X and Y.

asymptomatic Without symptoms.

Pedigrees of autosomal dominant and autosomal recessive diseases • Figure 20.10

A pedigree chart can show the frequency of a phenotypic trait in successive generations. Pedigree charts can also simply show ancestry—a family tree is a kind of pedigree chart. These kinds of pedigree charts are most commonly used when studying the ancestry of humans, horses, and show dogs.



Some Traits Are Sex-Linked

Humans have one pair of chromosomes, called the sex chromosomes, that do not match in terms of size or content. The sex chromosomes include the large X chromosome and the smaller Y. These two determine gender. If a Y chromosome is present during development (XY), the fetus will become a male. If there is no Y present (XX), the fetus becomes female.

Females have two copies of every gene on the X chromosome. Since only one copy of each allele is needed during normal growth and development, one X chromosome is randomly shut down. This shutdown occurs during development, leaving one condensed X chromosome as a **Barr body** within the nucleus. All the cloned progeny of this cell get the same functional X and the same Barr body. Thus, human females consist of patches of genetically distinct tissues, based on which X is inactivated. This patterning is called mosaicism. During development, the alleles on the active X chromosome are expressed and those on the inactivated X are repressed. Differences in the alleles carried on the two X chromosomes are markers for these cloned cell populations. In some organisms, this mosaic patchiness is easily discerned. For example, the patchiness of coat color in female calico cats is due to mosaicism in their tissues. One X chromosome carries the allele for black fur, and the other carries the allele for orange tiger-striped fur. Clones of each cell type express the allele they carry, resulting in patches of different fur colors. (The white color is carried on a separate chromosome.)

The Y chromosome contains few functional genes. The Y chromosome includes few functional genes, with the most recent count coming to just 78 genes. It was previously assumed that there were no genes of consequence on the Y chromosome, but as the number of genes identified increases this seems illogical. Scientists are just beginning to understand the significance of the Y chromosome genes to the male. Only one, the **SRY** gene, codes for male anatomical traits. The remaining Y chromosome genes are "housekeeping" genes—genes that are active in most body cells and do not confer male characteristics.

None of these genes have specific homologous counterparts on the X chromosome. This is a potential problem during nuclear division, as the Y chromosome cannot condense and pair up with the X chromosome in the same fashion as autosomal chromosomes. Instead, the Y chromosome includes a series of **palindromes** that allow it to fold back on itself during cell division. With limited ability to cross over during meiosis or to silence dysfunctional genes on either the X or the Y chromosome during development, mutations are more often retained and expressed in the developing male. In females, having two copies of the X chromosome with all of its genes doubles the chance of expressing a functional allele. The male, however, has only one X chromosome. The alleles on that single chromosome must be used even if they are slightly defective.

palindrome A group of nucleotides with the same sequence when read in either direction (for example, CGTTGC).

Genes carried on one sex chromosome with no counterpart on the other sex chromosome code for **sex-linked traits**. Because there are so many more functional genes on the X chromosome than on the Y, these are the genes usually referred to when discussing sex-linked traits. Characteristics carried on the X chromosome include color blindness and hemophilia. See Figure 20.11.

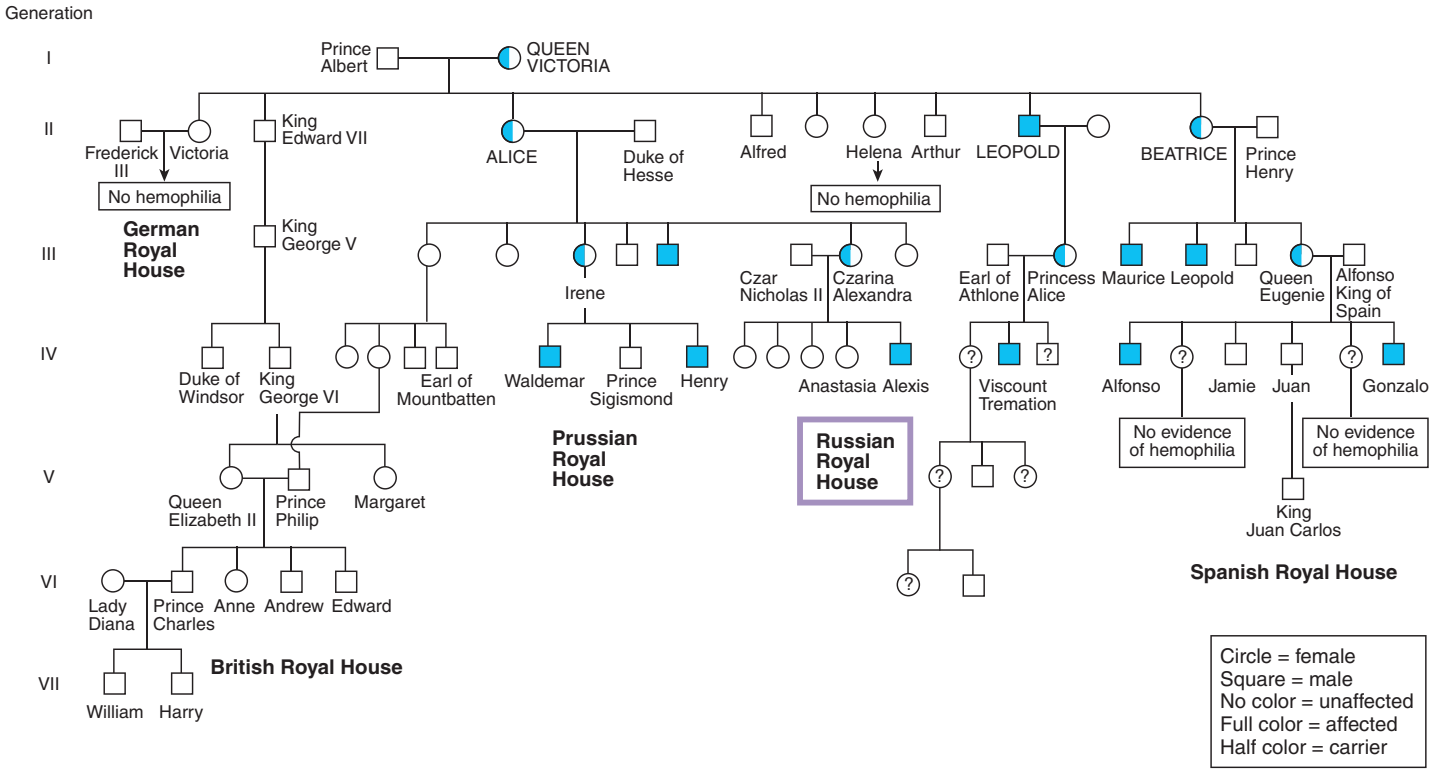
Females are mosaics, males are not. As discussed, the X chromosome carries many more genes than the Y. The female embryo has two X chromosomes, but one randomly shuts down in each embryonic cell early in development. The same X chromosome is active in all daughter cells of any particular embryonic cell, creating a situation in which female body cells have two distinct genetic lineages.

Biologists call such a person a mosaic, and the different expression rates of alleles on the X chromosomes can have visible and invisible consequences. Female humans are mosaics, and this affects traits coded by the X chromosome. The varying proportion of each particular X chromosome in the adult tissues of the female may explain why the onset and intensity of X-linked genetic diseases vary more in women than in men.

Because males have only one X chromosome, any defective gene on it can cause disease. Scientists say this explains why males have higher rates of X-chromosome diseases, such as Duchenne muscular dystrophy and hemophilia. Paradoxically, having only one X chromosome may have accelerated evolution among males. X-linked diseases can be powerful enough to kill males in utero or before reproductive age, which helps remove the defective genes from the population. In evolutionary terms, a weakness for the individual becomes a strength for the group.

Pedigree of hemophilia in the royal family of Queen Victoria • Figure 20.11

People with hemophilia have blood that is deficient in a clotting factor necessary for proper wound healing. This deficiency leads to slower than normal blood clotting and is due to an X-chromosome disorder that results in a deficiency of blood-clotting compounds. Females are the carriers of the disorder, which shows up in males (most commonly). Queen Victoria was a carrier, so each of her daughters had a 50% chance of being a carrier as well, and 50% of her sons had a chance of being a hemophiliac. Her carrier daughter Alice introduced the allele into the Prussian and Russian royal dynasties, and her carrier daughter Beatrice brought the allele into the Spanish royal dynasty. The current British royal family is, fortunately, unaffected.



Sex-influenced traits are carried on autosomal chromosomes but are more common in one sex than in the other. Hormonal differences between the two genders are most often responsible for the altered expression of these genes.

Genetic Variations Are Usually Caused by Mutations

Many of the genetic variations we see in the human species are due to mutations that have been perpetuated in small, often isolated populations. Human populations, just like any animal population, will undergo more rapid **evolution** when they are reproductively isolated. Language and ethnicity can isolate human populations, even those that live in close physical proximity. Geographic structures, such as mountains, deep valleys, or broad deserts, can also isolate human populations. Despite isolation, humans exhibit a range of expected phenotypes. For example, natural skin tones range from extremely pale tan to very dark brown. People are NOT blue, right? Wrong! Amazingly, a group of people in Kentucky occasionally produce a blue child—see *What a Scientist Sees: The Blue People of Troublesome Creek*, on the next page.

evolution Descent with modification.

Genetic Counseling Can Help Avoid Chromosomal Disorders

Genes and chromosomes can be damaged during cell division. Errors can occur in an entire chromosome, part of a chromosome, or a single gene. Gross errors, called chromosomal disorders, include variations in chromosome structure or number. These disorders include Down syndrome and fragile X mental retardation. According to the March of Dimes, chromosomal disorders affect about

WHAT A SCIENTIST SEES

The Blue People of Troublesome Creek

What is going on? These children are born the color of a bruised plum, and often they retain that color into adulthood. Some appear blue only when angry or cold.

The people of this area of Kentucky are all descendants of Martin Fugate, a French orphan, and his red-headed American wife. Against all odds, both Martin and his wife carried a recessive gene coding for a nonfunctional enzyme in the blood. Methemoglobin is a blue precursor to normal hemoglobin that is present in small amounts in blood. Usually, the enzyme diaphorase converts methemoglobin to functional hemoglobin, restoring blood's red color. These people in Kentucky cannot convert methemoglobin to hemoglobin, resulting in that blue coloration to the skin and mucous membranes. Geographic barriers have isolated the population with the "blue gene" to the Troublesome and Ball Creek valleys.

Happily, modern medicine can correct the blue color, allowing these people to lead normal lives, but the allele remains in the population. This strange phenomenon clearly demonstrates that inheritance and evolution follow the same rules in humans as in other animals. Genes carry traits, and traits can be either lost or enhanced in populations.

Think Critically

1. Can you find any evidence in this description that the defective diaphorase gene is either a sex-linked or a sex-influenced trait? What type of evidence would you look for?
2. How might you help couples in this area determine their probability of producing a child with abnormal blue coloration?
3. How might scientists have discovered that both Martin Fugate and his wife carried this recessive gene? What tool could demonstrate the beginnings of this trait?

7.5% of fertilizations, but many cause extreme deformities. Because many defective embryos abort spontaneously, only about 0.6% of live births show genetic defects due to chromosomal disorders. Just as it can be heartbreaking to lose a baby during pregnancy, it can be difficult to raise a child born with a **congenital** defect. Most babies born with congenital defects can trace their problems to a single gene carrying a dangerous recessive or dominant allele. Therefore, the chances of conceiving a child with a congenital defect caused by alleles can be predicted with the Punnett square.

congenital A condition that is present at birth because of genetic or environmental factors; usually detrimental.

Genetic disorders may also result from the interaction of genes and the environment. Other genetic disorders are caused by a series of alleles spread over several genes, which, if present in one individual, lead to the expression of a genetic defect. These defects depend on the interaction between several genes and the environment. These **multifactorial disorders** include cleft lip and palate, rheumatoid arthritis, epilepsy, and bipolar disorder. Simple traits, such as skin color, hair color, and weight, are also multifactorial traits. As you know from observing these traits in your

multifactorial disorder Genetic disorder due to a combination of genetic and environmental factors.

Genetic disorders, their symptoms, and their predominant carriers **Table 20.3**

Disorder	Type	Symptoms	Carriers/Type of disease
Huntington's disease	Chromosome abnormality	Affects the brain, causing poor memory, lack of coordination, mood swings, lack of fine motor control	Autosomal dominant disease
Turner syndrome	Chromosome abnormality	Short stature, improperly developed ovaries, stocky appearance, webbed neck, low hairline	Missing or incomplete X chromosome (XO female)
Klinefelter syndrome	Chromosome abnormality	After puberty, males develop breast tissue, have less muscle mass, and have little facial hair	XXY males
Cri-du-chat syndrome	Chromosome abnormality	Distinctive cry due to abnormal larynx development, low birth weight, microcephaly, heart defects, facial deformities	Deletion in chromosome 5
Phenylketonuria	Single-gene disorder	Severe brain damage, epilepsy, eczema, microcephaly, and a musty body odor	Autosomal recessive
Severe combined immunodeficiency disorder (SCID)	Single-gene disorder	High rate of infections soon after birth, including pneumonia and meningitis	X-linked recessive trait
Sickle cell disease	Single-gene disorder	Loss of function in organs where oxygen delivery is compromised; shortened life span	Autosomal recessive trait
Cystic fibrosis	Single-gene disorder	Coughing, wheezing, respiratory illnesses, salty-tasting skin, weight loss	Defective gene on chromosome 7; autosomal recessive
Marfan syndrome	Single-gene disorder	Connective tissue disorder causing excessive growth with little strength, long fingers, toes, and shins, weak heart valves	Autosomal dominant disease; defective gene on chromosome 15

own family, the inheritance of multifactorial traits is most apparent in the immediate generation. As individuals become farther removed from the affected individual (the carrier), the trait disappears. As an example, your hair color is probably closer to your parents' hair color than to your great-grandparents'.

Sometimes, unpredictable genetic disorders, caused by mutations or improper meiotic divisions, appear in families. Mutations occur with amazing frequency, at an estimated rate of about 1 misplaced base per 50 million nucleotides. That works out to 120 mutations per new cell. Although several enzymes "patrol" your DNA looking to repair these errors, and natural selection is constantly trying to delete defective genes from new generations, the system is not perfect. However, with our increasing knowledge of genetics, potential parents have tools at their disposal that take some of the guesswork out of producing healthy children. One option is the time-tested "let's fall in love, get married, and take our chances" approach. Some couples, however, are more interested in taking control of their genetics. For these people, genetic counseling is a great choice.

Table 20.3 lists some of the many genetic disorders that are discussed in genetic counseling.

Tay-Sachs disease results from a defective allele. Certain religious or ethnic groups have a higher proportion of detrimental recessive alleles than others, because their populations intermarry more than other groups. Ashkenazi (north European) Jews and French Canadians, for instance, have a higher likelihood of carrying the recessive allele for Tay-Sachs disease. Tay-Sachs is a fatal disease caused by a dysfunctional lysosomal enzyme in the brain.

Usually, neurons create fatty substances that are easily removed from the brain by lysosomes. In Tay-Sachs, the allele that codes for the enzyme that breaks down these fatty substances is defective, so the fats build up. The affected homozygous recessive individual develops normally until age 4, but brain function then deteriorates rapidly. The gene for this defective lysozomal enzyme is recessive, so phenotypically normal heterozygous carriers are not aware that they are carrying this potentially lethal mutation.

Sadly, up to 1 in 25 Ashkenazi Jews are thought to be carriers. When marrying within the faith, Ashkenazi Jews often request a compatibility score from a genetic counseling service, which will indicate the probability that their child would have Tay-Sachs. This type of testing has caused a dramatic reduction in deaths due to Tay-Sachs.

Prenatal Testing Raises Questions

Rapid advances in genetics have raised the promise—or the peril—of studying the genetics of children yet to be born. Already, prenatal ultrasound can reveal the sex of a fetus, and some parents in the many cultures that favor male babies have responded by aborting female fetuses. This practice has increased the ratio of male to female children in China and perhaps elsewhere.

As you remember from Chapter 19, prenatal genetic testing can take two forms: testing the developing baby with chorionic villus sampling or amniocentesis, and testing the genes of potential parents. Each process raises questions. See *I Wonder… Can We Create Super-Babies?* to investigate one such question.

Prenatal genetic sampling can detect chromosomal abnormalities. Prenatal genetic sampling is done primarily to detect chromosomal abnormalities, such as Down syndrome, and focuses on women age 35 or over who are more likely to have children with these abnormalities. These genetic problems cannot be corrected, and the parents must either abort the "defective" fetus or understand and accept the challenges of raising such a child. If a problem is discovered, at the very least the test results can alert the parents to their future child's special needs. Any benefits

I WONDER...

Can We Create Super-Babies?

Do you want a child with dark hair? Musical talent? Muscular stamina? As we learn more about the human genome, we come closer to understanding just how traits like these are inherited. Originally, the human genome was mapped in order to identify those genes related to disease. Once these genes were located, the genomes of at-risk people could be scanned to determine whether they carried the same deleterious gene. For many of these genes, identification amounted to looking for uncommon SNPs or single nucleotide polymorphisms. These are areas in the human genome that differ among individuals by only a single nucleotide (A, C, T, or G). SNPs normally occur every 300 bases or so. Researchers have found that SNPs occurring within genes or their regulatory areas often lead to a higher susceptibility of disease, and therefore they use these SNPs to "mark" disease susceptibility. With the human genome project completed over 8 years ago, scientists have had access to our genome and its many SNPs for almost a decade. We can now identify genes that code for traits and behaviors not related to disease. Most personality traits are produced by a group of genes, working together and interacting with the environment to produce phenotypic results. Despite this complication, some interesting traits have been linked to specific genes. As of late 2008, the genes that code for handedness, eye color, addictive behavior, and athleticism were identified. As recently as 2005, muscular strength was discovered to be "marked" by a series of SNPs, just like disease susceptibility. Of course, the manipulation of the human genome leads to many unexpected scientific questions. Genes often have more than one effect on phenotype. For example, the gene that codes for increased memory and enhanced learning was also discovered to code for increased pain sensitivity in laboratory mice. At the current time, we have the knowledge to identify many deleterious and beneficial traits. We also have the ability to select for or against these traits in pre-implanted embryos through the GIFT program. Can we create a super baby? Potentially, yes. But should we?

of these tests must be weighed against the chance that the invasive sampling itself will harm the fetus. In the future, as the knowledge of genetics increases, we may see sampling of the embryo itself, in the hope of intercepting genetic diseases even earlier.

Genetic testing can be used even before conception. A more complicated set of ethical questions arises when parents want to analyze their own genes before conception. In a few cases, the need for such analysis is clear and convincing. If a genetic disease like the deadly nerve disorder Huntington's disease runs in the family, parents might want assurance that they will not pass the gene to their children. If testing reveals a high probability of their passing on this disease, the would-be parents may want to avoid pregnancy.

Genetic situations can also present confusing ethical decisions, especially now that scientists are detecting the genetic components of dozens or even hundreds of diseases and conditions. Many of these genes do not amount to a death sentence. Would a genetic predisposition for cancer matter if the gene raised the child's risk of cancer by 10%? What if it doubled the risk of cancer?

The picture is complicated now, and the only thing we can say for sure is that better knowledge of genetics will make the issue of prenatal testing even more complex. A strong basic understanding of human genetics will help prepare you to answer the difficult questions you may confront during your reproductive years.

CONCEPT CHECK STOP

1. **What** can be learned from a family pedigree?
2. **Which** chromosome carries the genes for sex-linked traits?
3. **What** is a chromosomal disorder and how does it relate to genetic counseling?
4. **What** are the values and costs associated with prenatal testing?

20.5 Biotechnology Has Far-Reaching Effects

LEARNING OBJECTIVES

1. **List** four biotechnologies used in modern research.
2. **Define** genetic modification and transgenic organism.
3. **Explain** how DNA is used in the courtroom.
4. **Describe** the outcome of the Human Genome Project.

DNA is DNA. When you work with it in the laboratory, it makes little difference where it came from, as all DNA is composed of the same four nucleotides, held in the same basic arrangement. What makes each organism—and each individual—unique is the sequence of nucleotides attached to the sugar-phosphate backbone.

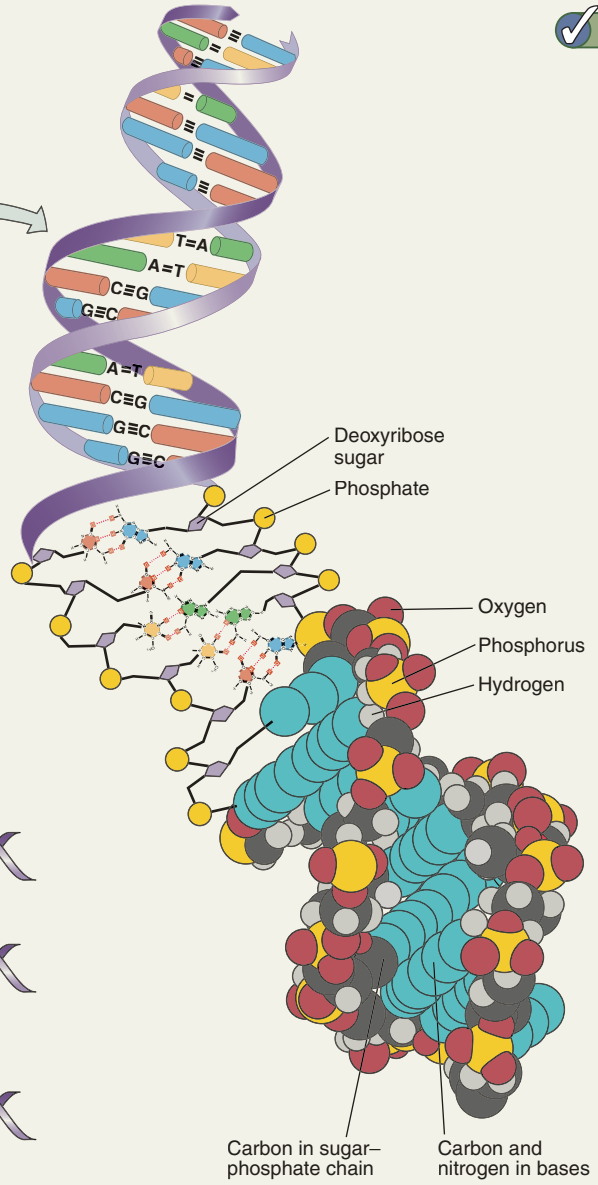
centrifugation
Rapid spinning of a sample to separate components by density.

To read the "language" of genetics, we must identify the sequence of bases encoded in DNA. The techniques used to isolate DNA and identify the base sequence include **nucleic acid hybridization**, **gel electrophoresis**, **PCR**, and **RFLP analysis**.

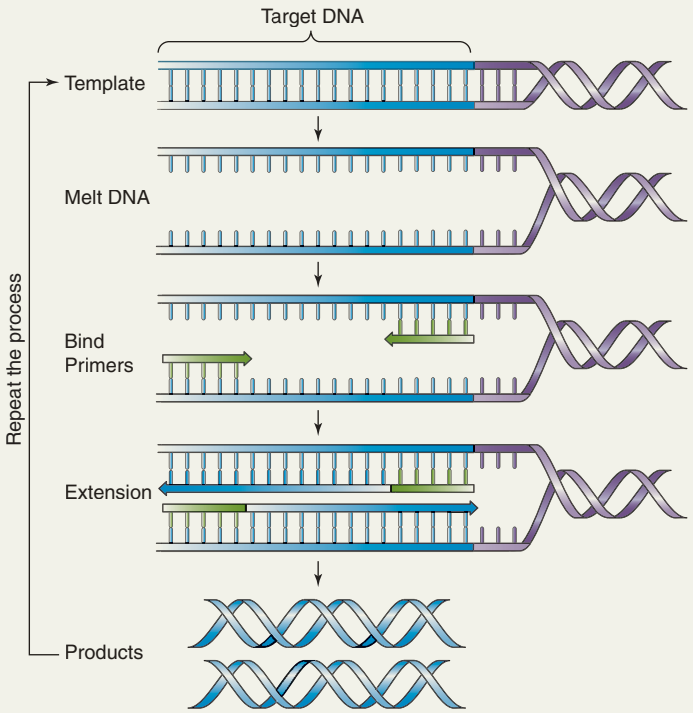
To isolate DNA from an organism, we pop the cell membrane and remove the nucleus. Through **centrifugation**, we separate the denser nucleus from the lighter organelles and cytoplasm, thus concentrating the DNA. With specific buffers and chemicals, we remove pure DNA from the nucleus. One of the simple techniques used to obtain a pure sample of DNA is to spin the impure DNA sample on a **cesium chloride gradient**. Pure DNA will form a band where its density matches that of the surrounding cesium chloride. The band can be visualized using the proper DNA staining techniques. Once located, the pure DNA can easily be removed from the cesium chloride gradient with a syringe. **Figure 20.12** shows some of the ways we work with DNA.

THE PLANNER

a. DNA can be isolated from living tissue by fractionating the cells (breaking them apart) and separating the components in a cesium chloride gradient. The DNA will band in one specific density within the gradient.



b. When it is removed from the gradient and viewed under an electron microscope, the typical double-helix shape of the DNA can be seen.



c. PCR is often used at this stage to increase the amount of DNA. The original DNA (template) is split apart using heat. The single strands of DNA are then exposed to RNA probes that will bind, or anneal, to specific complementary areas of the DNA. Transcriptional enzymes will elongate that bound RNA, creating new strands of DNA. Often the nucleotides provided in the elongation step are radiolabeled to allow experimental tracing of the newly created DNA pieces.

Purified DNA Can Be Used in Laboratory Procedures

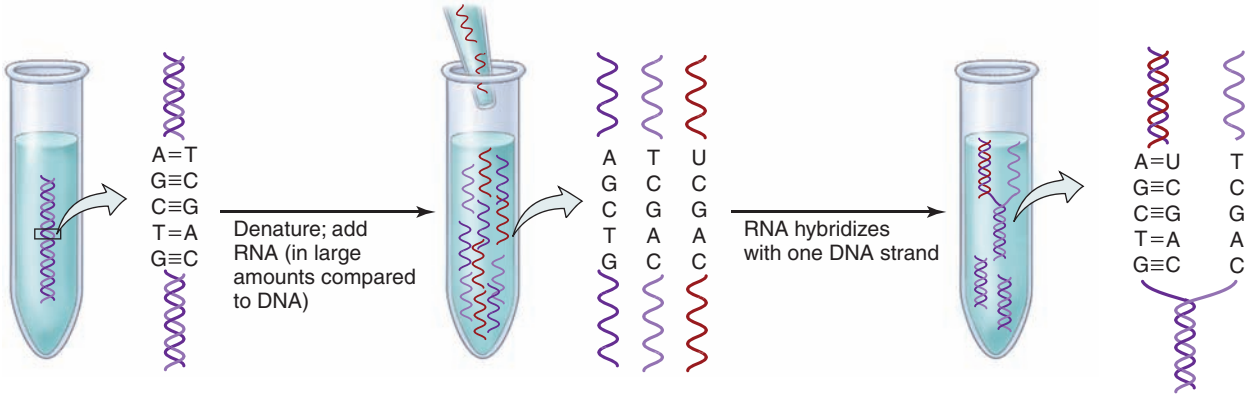
Once purified DNA is available, it is easy to work with in the lab. DNA behaves predictably. It is double-stranded, and the bases always pair up A to T and C to G. If conditions favor the **dissociation** of the strands, they will fall apart. Increased heat is one factor that causes dissociation. To **reanneal**, or reseal, the two complementary strands of DNA, we return the sample to body temperature. The result is of no major consequence if we merely split and then recombine the same pieces of DNA. However, if we add DNA from a different source or small pieces of RNA to the mix, things get more interesting. RNA will bind to the dissociated, single-stranded DNA where the bases match. This means that we can use specifically prepared RNA to locate genes for certain proteins on the DNA. The RNA can be engineered to base-pair with the original DNA and "tag" just about any sequence of DNA we wish to locate. DNA fragments can also be used to see how closely related two organisms might be. By isolating DNA from both organisms, dissociating the strands, and then mixing the dissociated strands together under reannealing conditions, it is possible to see just how similar those two organisms' DNA are. If the organisms share a common ancestor and are very closely related, large portions of their DNA will stick together. If the two organisms are not very similar, their DNA will not anneal. See Figure 20.12.

Insulin was the first human gene identified. How were scientists able to locate the gene for insulin on the human genome? Return to the central dogma and play the mental game of working backward from the protein to the DNA sequence that codes for it. To do this, we must first choose a protein and determine the amino acid sequence. Insulin was the first human protein sequenced. Because of its relatively simple construction and the ease with which insulin could be harvested, it became the first protein used in this "identify the DNA sequence that codes for the protein" technology. It is a relatively small protein, composed of two polypeptide chains. The first chain has only 21 amino acids and the second has 30.

The protein sequence unlocks the DNA sequence. To sequence a protein, we chemically disassemble it and identify each amino acid as it comes off. Because each amino acid is coded for by a specific three-base codon, we can recreate the tRNA molecules that created the original protein. Working backward using a codon table, the amino acid sequence gives us the sequence of tRNA molecules that created the protein. This process is the reverse of translation. Going back another step, we take the tRNA anticodon sequence and rebuild the necessary complementary mRNA codon sequence. We can then build this mRNA sequence in the laboratory, which we often "label" with a radioactive compound. The radiolabeled mRNA will bind to its complementary spot on the DNA. Once you locate the radioactive label, you have identified the exact spot on the chromosome where DNA and mRNA are complementary. See **Figure 20.13**. That spot is the location of the gene for your original protein. Scientists now have followed this process for many of our proteins, giving us a good map of the location of many of our genes.

Insulin mapping • Figure 20.13

Denatured DNA is mixed with the radiolabeled mRNA strand created in the laboratory from an analysis of intact insulin. The spot where the radiolabeled mRNA hybridizes with the DNA is the exact location of the gene for insulin.



Restriction Enzymes Are the "Scissors" of Biotechnology

Once we locate a gene, we often want to isolate it, or cut it away from the adjacent DNA. In 1970, two scientists simultaneously discovered that bacteria carry enzymes that can cut DNA at specific palindromes. These enzymes are "restricted" to acting only at a specific sequence of DNA bases. These so-called **restriction enzymes** act as a kind of immune defense for the bacteria. Because they cut only sequences of DNA that are not found in the bacterial chromosome, they destroy foreign DNA, such as that from an invading virus. Figure 20.14 shows a restriction enzyme in action.

In 1970, these two scientists, Howard Temin and David Baltimore, purified a second type of nucleotide-altering enzyme: **reverse transcriptase**, an enzyme with **polymerization** properties opposite those normally found in eukaryotic cells. Reverse transcriptase is able to produce DNA from RNA templates, reversing the usual transcription sequence of creating mRNA from a DNA template. Their understanding of this enzyme, combined with the discovery of restriction enzymes, opened a whole new area of molecular biology, supplying the tools for precise DNA manipulation.

polymerization The chemical bonding of monomers to form a larger molecule.

New genes can be spliced into existing chromosomes.

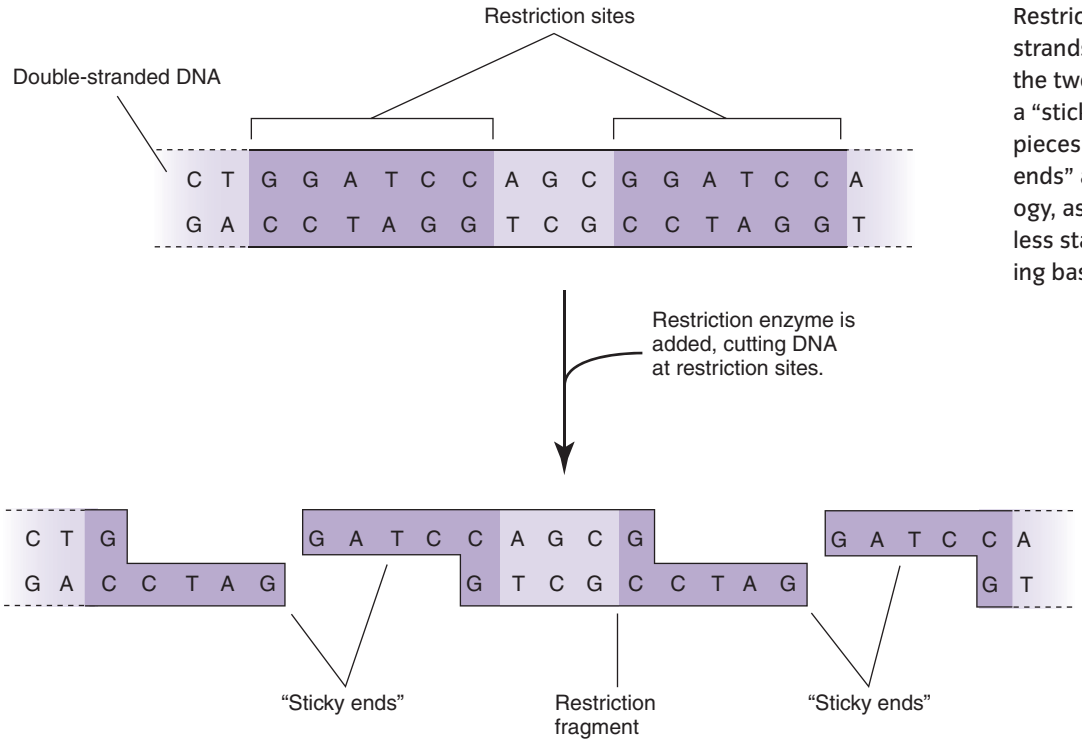
By cutting DNA between known sequences of bases and mixing these cut pieces with other pieces of cut DNA having matching ends, new genes can be **spliced** into existing chromosomes.

Just two years after the Temin–Baltimore discovery, Paul Berg at Stanford University used restriction enzymes to create the first **recombinant DNA** molecule. Berg first purified the DNA he was interested in, then cut it with a restriction enzyme to open a slot for the new gene. Next, he went to a different source of DNA and cut out the gene he wished to **transpose**, or move, using the same restriction enzyme. This step ensured that both types of DNA had matching "sticky ends." He inserted the new gene into the DNA by mixing the cut gene with the cut DNA and adding **ligase.** Ligase is an enzyme that seals and repairs DNA by reforming broken linkages between the phosphate groups

spliced Joined together; two pieces of DNA artificially joined together to form new genetic combinations.

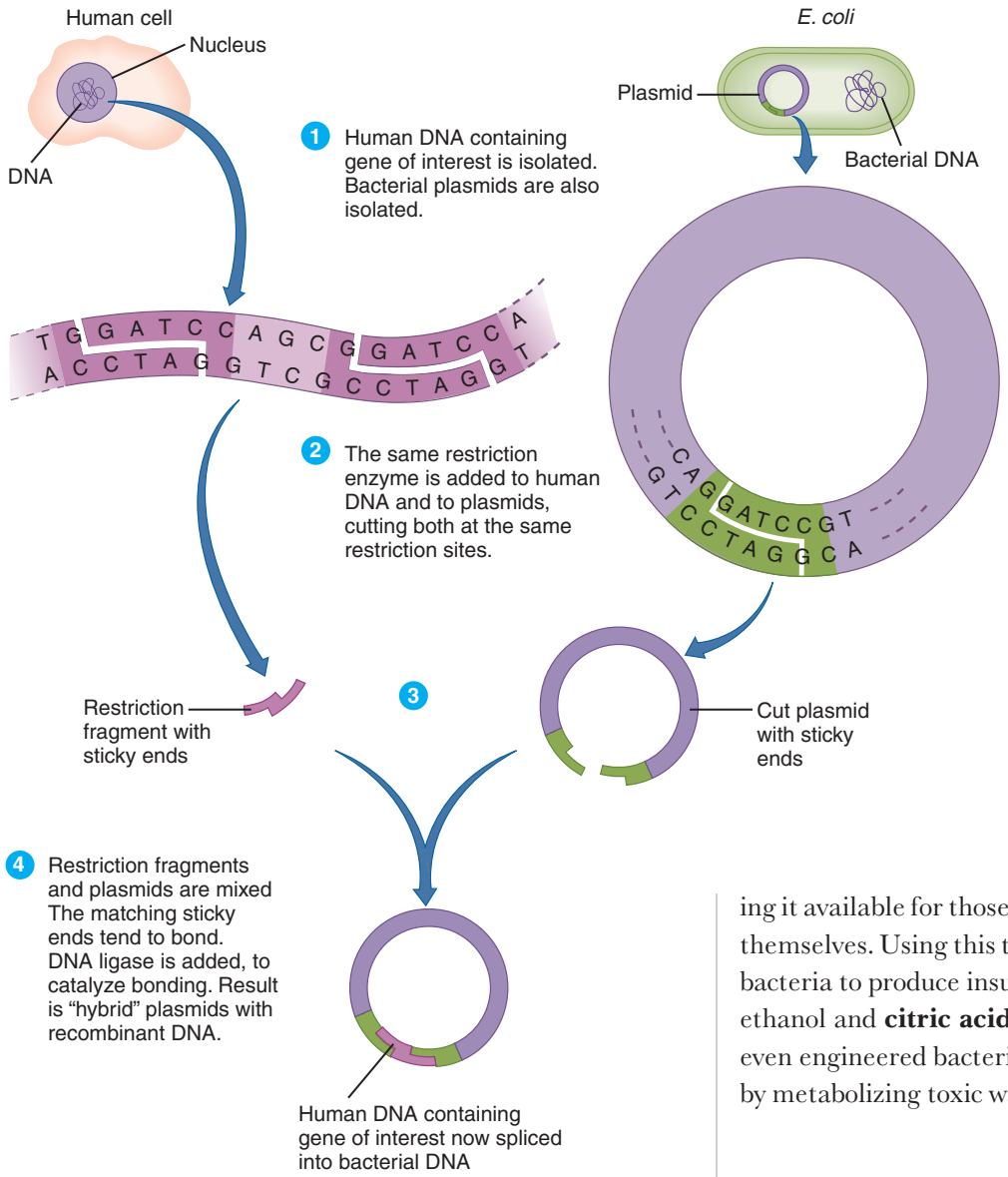
recombinant DNA The product of splicing genes.

Restriction enzyme action • Figure 20.14



Restriction enzymes can cut the DNA strands to leave a blunt end, where the two pieces are the same length, or a "sticky" end, in which the resulting pieces are of different lengths. "Sticky ends" are more useful in biotechnology, as the resulting pieces of DNA are less stable and will reunite with matching base pairs to seal the uneven ends.

Restriction enzymes at work • Figure 20.15



and the sugars in the backbones. This process was an early use of biotechnology, and what Berg created with his recombinant DNA was the first **transgenic** organism.

transgenic Type of organism with a gene or group of genes in its genome that was transferred from another species or breed.

plasmids Circular pieces of double-stranded DNA outside the nucleus or the main DNA of the cell.

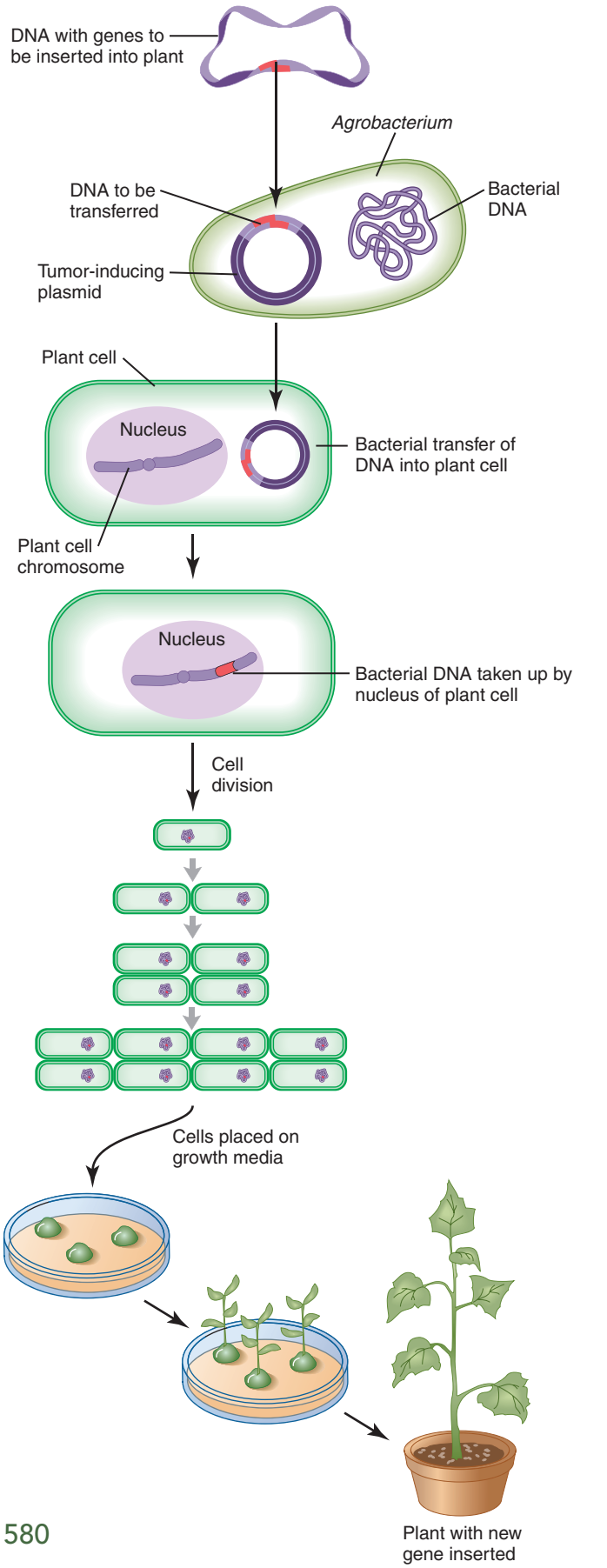
Recombinant DNA technology is common. Recombinant DNA technology is now common and is often used to insert human genes into bacterial **plasmids** (see **Figure 20.15**). If inserted properly, the modified bacteria will produce the human protein in large quantities, making it available for those people who cannot make the protein themselves. Using this technique, scientists have engineered bacteria to produce insulin and vaccines and to manufacture ethanol and **citric acid** (a natural preservative). They have even engineered bacteria that can clean up the environment by metabolizing toxic waste or petroleum spills.

Transgenics and Clones Are Part of Our Brave New World

The first artificial transfer of genes—transgenics—occurred in bacteria, but by carefully timing the introduction of the DNA, genetic engineering of plants and animals is also possible. One way to alter plant DNA is to use a **vector**, such as bacteria that naturally infect the plant, to carry the new gene into the cells. The bacteria are first infected with a plasmid carrying the gene to be inserted. Embryonic plant cells are grown with the transgenic bacteria, and occasionally some plant cells pick up the plasmid, as seen in **Figure 20.16**.

Alternatively, embryonic plant cells can be shocked with high voltage in the presence of the plasmid. As the cells respond to the electric shock, the plasmid is incidentally

Gene transfer using a bacterial vector • Figure 20.16



incorporated. Another route is to affix the DNA to a microscopic metal sphere and literally shoot it into embryonic plant cells, using a sterile modified gun in the laboratory.

Viruses can be used in transgenics. Viruses can also be used to alter host cell DNA. The virus itself must be transformed, removing the pathogenic genetic material from within the viral coat and replacing it with the gene of interest. When the transformed virus infects the plant, it injects the gene of interest into the plant cells, rather than the pathogenic viral genes. Hopefully, the new gene will incorporate into the plant DNA just as the original viral genetic material would have.

Transgenic plants are all over the world. All of these methods have been successfully used to create transgenic plants, with Monsanto Corporation, Syngenta, and Pioneer Hi-Bred International taking the lead in the production of transgenic corn, rice, cotton, and soybeans. These crops are catching on quickly around the world. In corn and cotton, genetics engineers have added bacterial genes that impart insect resistance. Corn and soybeans have received a gene that makes the plants resistant to glyphosate, a popular and relatively nontoxic herbicide. There may be unintended and unrecognized consequences of these manipulations, which is why some scientists as well as many other people are uncomfortable about the increasing popularity of transgenic crops.

Genetic engineering can also be used to alter the nutritional properties of a food. Scientists have added a gene for beta carotene, a yellow nutrient that is lacking in the diet of many people in Third World countries, to rice. This "golden rice" was engineered to help alleviate malnutrition by supplying a raw material for vitamin A in a common food source. The diversity of this concept allows for some fantastic research programs. For example, researchers are working to introduce genes that direct edible plants to produce vaccine proteins. Eating the raw plant would then provide both plant nutrients and a dose of vaccine. It sounds good, but producing vaccines and other custom-made proteins also raises major public health concerns. If food plants start producing vaccines, medicines, or industrial products, how can we absolutely prevent food contamination with medicines or industrial chemicals? Can we ensure that the vaccine producers will remain separate from the "normal" produce? See *Health, Wellness, and Disease: Are Genetically Modified Foods Safe for the Environment? Are They Healthy to Eat?*

HEALTH, WELLNESS, AND DISEASE

Are Genetically Modified Foods Safe for the Environment? Are They Healthy to Eat?

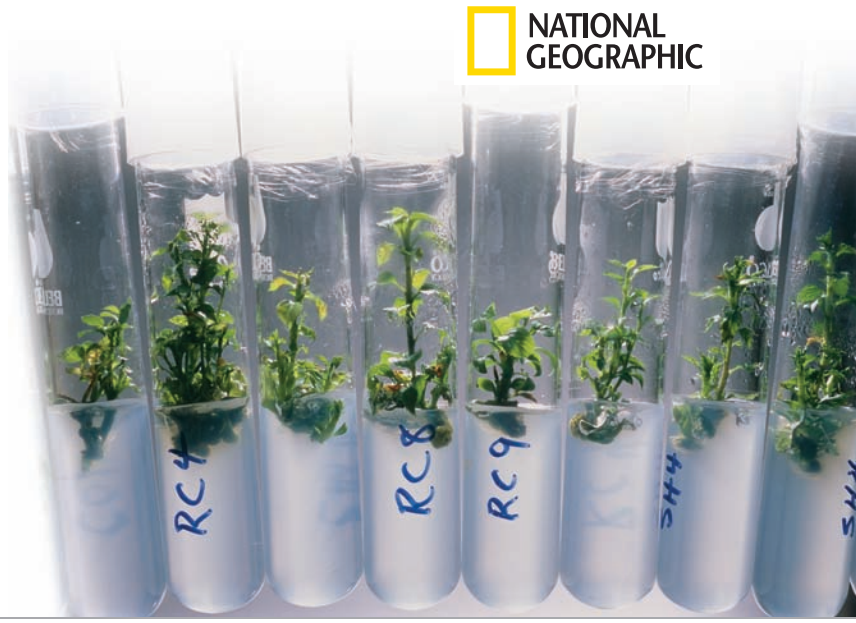
THE PLANNER

If you ate a food containing corn or soybeans today, you probably ate genetically modified (GM) food, unless the food was labeled as "all organic," which by definition does not contain genetically engineered ingredients.

For more than a decade, questions have swirled around GM seeds. Advocates say that moving genes from other organisms can improve the resistance of plants to insects and disease, raise yields, allow cropping on marginal land, increase farmer profits, and improve nutrition. They also stress that farmers have been altering genes in their crops since the dawn of agriculture.

Critics dispute many of these claims. To date, yield improvements have been slight. No transgenics have yet been approved for salty or droughted soils. Also, golden rice, with its high level of vitamin A, has not yet begun to prevent the blindness caused by shortages of vitamin A in developing countries.

Critics also say that transgenics could pose threats to human health. For example, several years ago, a seed company transferred a gene from the Brazil nut into soybean, in an effort to make the protein more complete. Before the seed reached the market, the company discovered that the crop would trigger food allergies among people allergic to nuts. The seed company halted the research project. Although this story may seem innocuous, in September 2000 StarLink corn was leaked into the food supply. StarLink was created as cattle feed and was never approved for human consumption. In fact, it was later discovered that StarLink corn caused allergic reactions in those who consumed it. Many people suffered, leading to lawsuits, illnesses, and general fear of GM foods.



Transgenic animals are harder to produce. Transgenic animals are more difficult to produce than transgenic plants, as animal cells do not take up genes as readily as bacterial or plant cells. Viral vectors are the most promising route of introducing foreign genes into animal cells to date. Once a transgenic animal cell is created, it must be cloned to produce a line of identical animals and, once again, cloning animals is far more difficult than cloning plants or bacteria.

Usually, transgenic animal cells are created by inserting a gene into a fertilized egg. If the gene is taken up, it will appear in every cell and hopefully will be expressed as intended. Although this sounds simple, it is not. Often, transgenic animals are sterile, requiring that they be cloned to reproduce, which introduces another level of technological difficulty. In 1998, researchers at the University of Hawaii, Manoa, cloned 50 transgenic mice from adult cells after years of failures, giving the mice a gene for a green fluorescent protein as a marker that they were, in fact, cloned. All 50 mice glowed green under UV light.

The Honolulu method, as it is called, was a simplification and blending of two methods already in use and sparked renewed interest in animal transgenics for pharmaceutical use as well as livestock improvement. This simple procedure has been a boon to genetic technology and has been used to create larger cloned animals.

Where can this technology lead? The guar is an extremely rare animal living in India. Scientists have attempted to clone a guar into a cow egg using older fusion methods. Should they again have the opportunity to harvest cells from this endangered animal, the Honolulu method may provide a larger percentage of living embryos, perhaps leading to a successful cloning. With only 90 of these organisms left in the wild, genetic engineering might be their only chance.

Gene Therapy Can Correct Defects and Treat Disease

As genetic engineers work on cloned and transgenic animals, health researchers are also considering a less drastic step—**gene therapy** for humans. In transgenic animals, the entire animal gets a new gene, which is first inserted into the fertilized egg. In gene therapy, genes are inserted into specific cells to correct defects or treat disease. Defective or inactive genes are supplemented with active, functional copies of those genes in the adult human. Many difficulties could arise from this seemingly simple idea. An astronomical number of cells might need to express the gene. How could we get the gene inserted properly and ensure that it is working correctly in all of those cells?

One answer is to use viruses as vectors for gene insertion. As discussed previously, viruses normally inject their pathogenic DNA into the host's chromosomes, either directly or through reverse transcription of the viral RNA in retroviruses. Removing the pathogenic viral genes and inserting transgenes takes advantage of this viral mechanism. The viruses become tiny gene therapy injectors, delivering their modified and now helpful genetic contents to cells. Of course, these viral particles cannot reproduce in the cells, limiting the number of cells that can be "infected."

Gene therapy for human disease is fraught with trouble. Even after succeeding in the daunting task of getting the modified gene to the necessary cells, another issue remains. Unless the gene was inserted into the patient's germ cells (gamete-producing cells), the children of these genetically altered adults would likely have the same genetic defect and the disease, meaning they might also need gene therapy. On the positive side, gene therapy was successfully used to treat a four-year-old child who was unable to produce an enzyme that caused a severe immunodeficiency. Following closely on that success, in 2008 more than 180 clinical trials using gene therapy were under way in the United States. In April 2008 gene therapy was used to successfully treat a type of inherited blindness, and in 2009 genes that code for proteins that destroy cancer cells were wrapped in nanoparticles and successfully delivered to those target cancer cells in mice. Thus far, it seems that gene therapy can be a successful treatment, but success remains elusive. It's fair to say that gene therapy has not met its early promise, and research is needed to understand why not.

DNA Technologies Can Be Used to Identify Individuals

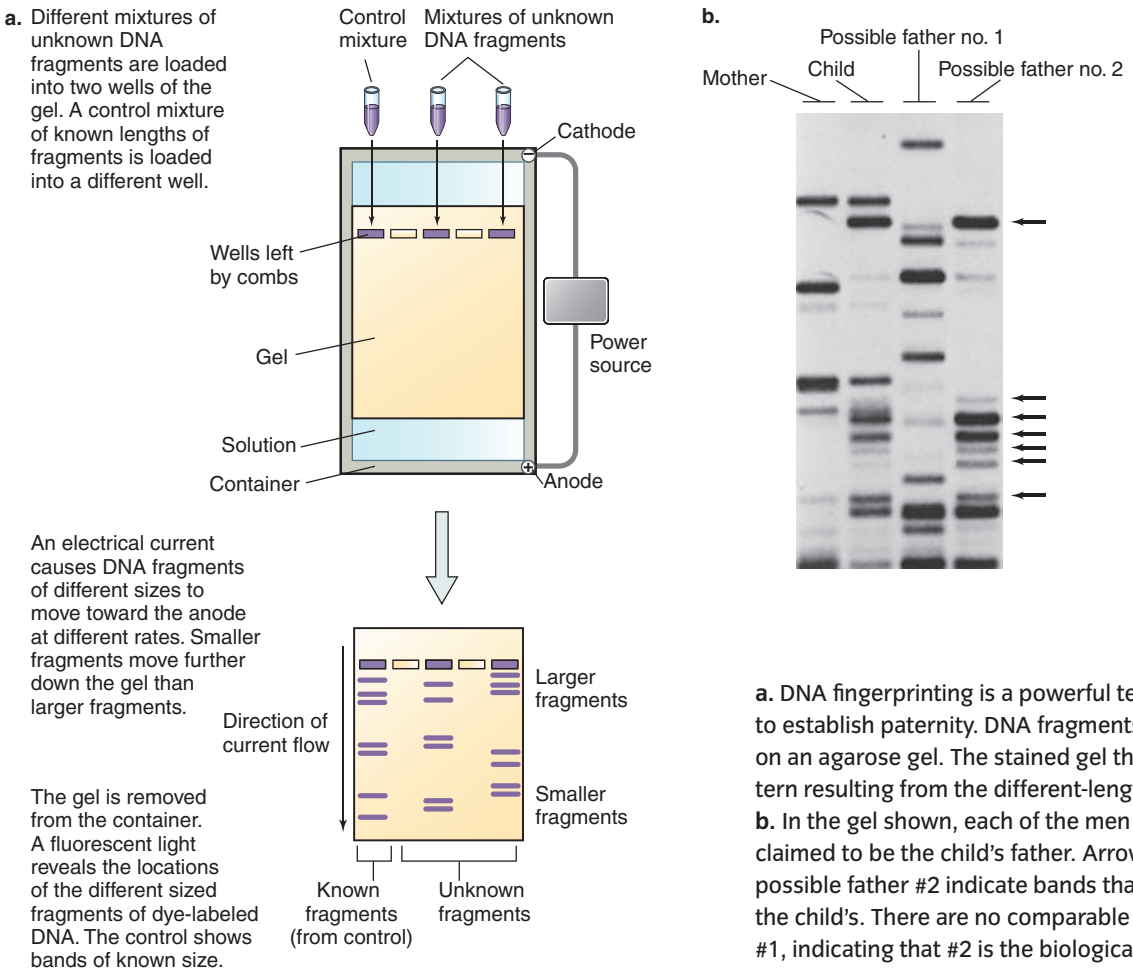
Applying DNA technology to societal needs rather than food or medicine, scientists have perfected ways to purify DNA from crime scenes, separate it into small pieces, and compare it to other DNA. The challenge in this research is to compare DNA from various sources in order to identify similarities. Many crime scene samples provide precious little DNA for examination. The DNA in a sample must be amplified to provide enough for the investigators to analyze. In 1983, in what some have called the greatest single achievement in modern molecular biology, Kary Mullis developed **polymerase chain reaction**, or PCR. Mullis worked for a biotech company and was probably not thinking about crime scene analysis, but his clever invention has brought the power of biotechnology to crime investigations.

Biotechnology helps solve crimes. PCR is a series of reactions that amplifies DNA using the same enzymes that cells use to synthesize DNA. You add a small amount of the sample DNA to a test tube, along with the four DNA nucleotides as building blocks, DNA **polymerase** (the enzyme that adds nucleotides during DNA duplication), **RNA** or **DNA primer**, and the appropriate buffers. You raise and lower the temperature in a precise sequence, and multiply the sample exponentially with each thermal cycle. Because DNA nucleotides pair with high fidelity, the resulting DNA is almost 100% identical to the original sample. This simple technique amplifies a small amount of DNA, providing enough of a sample to begin to analyze the base-pair sequence and match it with the DNA of crime suspects.

RNA or DNA primer A short segment of RNA or DNA binding to the original DNA strand, initiating DNA replication.

A large sample allows the next step in crime scene analysis: differentiating the DNA of several individuals. Much of the DNA in the human genome does not code for proteins and, because mutations and alterations in these regions do not affect function, they are highly variable. Each individual has a different sequence of DNA bases in these regions. Recall that restriction enzymes cut DNA only where they find their specific restriction site. In the variable regions of chromosomes, the locations of the restriction sites along the chromosomes change from one person to the next. Subjecting DNA to a variety of restriction enzymes should cut these variable regions of DNA in different places. Since we each have a unique series of nucleotides in our variable regions, each of us will generate

DNA fingerprinting technique and the resulting fingerprints of a mother, her child, and two possible fathers • Figure 20.17



a. DNA fingerprinting is a powerful technology that can be used to establish paternity. DNA fragments are electrically separated on an agarose gel. The stained gel then shows the banding pattern resulting from the different-length fragments of DNA. **b.** In the gel shown, each of the men whose DNA was tested claimed to be the child's father. Arrows pointing to the DNA of possible father #2 indicate bands that are the same as those of the child's. There are no comparable bands in the DNA of father #1, indicating that #2 is the biological father.

different lengths of DNA from samples cut with the same restriction enzymes. The resulting restriction digest is then analyzed to compare the lengths of the restriction fragments.

agarose A gel-like compound obtained from agar that provides a flexible, yet solid, medium for separation of DNA fragments.

Gel electrophoresis sorts out the DNA fragments. Separating these myriad cut pieces of DNA based on length allows us to view them as an organized group as we compare a suspect's DNA to samples from the crime scene. One easy way to view these fragment lengths is to spread them out based on size. Change-counting machines use this principle. It is hard to count the nickels, dimes, and quarters in one mixed pile of coins, but if you separate them by size and line them up in rows, it's suddenly quite easy. **Gel electrophoresis** does the same thing with pieces of DNA. The mass of fragmented DNA is loaded into the top well of an **agarose** gel. The gel is floating in a salt buffer, and an electrical current is passed through it. DNA, being slightly negative, is pulled through the gel toward the positive pole by the current.

Imagine racing alone through a crowded room, dodging chairs to reach the front of the room. If you then linked arms with four other people, the spaces between chairs would seem much smaller, and you would reach the front much later. The same principle holds for DNA moving through a gel. When a current is applied to the gel, larger fragments move more slowly, while smaller pieces race to the opposite end. The resulting separation of these pieces can be used to distinguish the various-sized DNA fragments created by the restriction enzymes, as seen in Figure 20.17. The name of this technique, **restriction fragment-length polymorphism (RFLP),** means just

that. Restriction enzymes create DNA fragments that are of different lengths in different individuals. Using gel electrophoresis, the pattern of those fragment-length polymorphisms becomes visible.

You have a unique DNA fingerprint. Running an RFLP on your own DNA will result in a unique sequence of DNA bands, all your own. This series of bands is your personal **DNA fingerprint**. Approximately one in one billion people will match your DNA fingerprint, unless you have an identical twin. Taking a sample of your DNA, exposing it to the same restriction enzymes, and running it on a gel next to the crime scene sample will allow comparison of your DNA to the DNA from the scene. If the banding pattern of each sample is the same, this is a sure sign that you were near the scene at some point, and you had best start working on an alibi! DNA fingerprinting can also be used to exonerate the innocent. In more than 100 capital cases in the past decade or so, "criminals" have been sprung from prison on the basis of DNA evidence. Many of these men had served more than a decade in prison for horrific crimes that they had not committed.

Though more expensive and time-consuming than traditional methods, DNA fingerprinting can also be used to establish paternity in rigorously contested cases. In that case, the infant's DNA fingerprint must show a high degree of similarity to both the maternal and real paternal fingerprints, demonstrating banding patterns that can be matched with either one parent or the other. The trouble with using DNA fingerprinting to identify paternity is that the baby's DNA will be a combination of maternal and paternal DNA, showing new banding patterns unique to the new individual. It is easier and more reliable at this point to match the infant's protein profiles with those of the father—for example, those proteins that appear on the red blood cells.

Perhaps the most famous use of DNA fingerprinting in the courtroom in recent history is the O. J. Simpson trial. At this trial, DNA evidence was ruled inconclusive because of questions concerning the quality and purity of the sample collection and the validity of the testing. This was certainly not the first time the technology had hit the courtroom floors, however.

The entire field of genetic research remained out of the courtrooms for many years after being introduced to the laboratory. Not until 1985 did genetic fingerprinting appear as legal evidence in court cases. The identification of large stretches of repeating patterns of DNA in the human genome had literally just occurred. Alec Jeffreys and his laboratory associates at the University at Leicester, UK, had no sooner discovered that these repeating patterns of DNA differed in length from one person to the next than the information was used in court. The relationship of a woman and a child needed to be established for an immigration case. Through RFLP analysis, the child was shown to be closely related to the woman. Using this evidence, the courts allowed the child to immigrate to the UK to be with her relative. As a matter of fact, Jeffreys coined the term *genetic fingerprinting* in his paper describing RFLP analysis as a sort of tongue-in-cheek joke.

Following closely on the heels of this case was the first murder case ever solved with genetic fingerprinting. In November 1987, Colin Pitchfork was convicted of the murders of two teenage girls in Narborough, Leicester. Whereas Colin was the first murderer to be convicted based on DNA technology, Richard Buckland was the first person to be exonerated of murder using DNA evidence. He was suspect number 1 in the Narborough case, but his DNA banding patterns did not match those at the crime scene at all.

Judges and juries need to know their genetics. Judges and juries are now frequently trying and hearing cases based on DNA and genetic evidence. They need to know how to weigh that evidence. They need to know that genetic scientists often deal in probabilities, not certainties. "Truth" often has to give way to careful analysis and most probable causes and effects. Also, the courts are beginning to see the defense "my genes made me do it—I had no choice." If that defense becomes more common, crime and punishment will never be the same.

The Human Genome Project Mapped Human Genetics

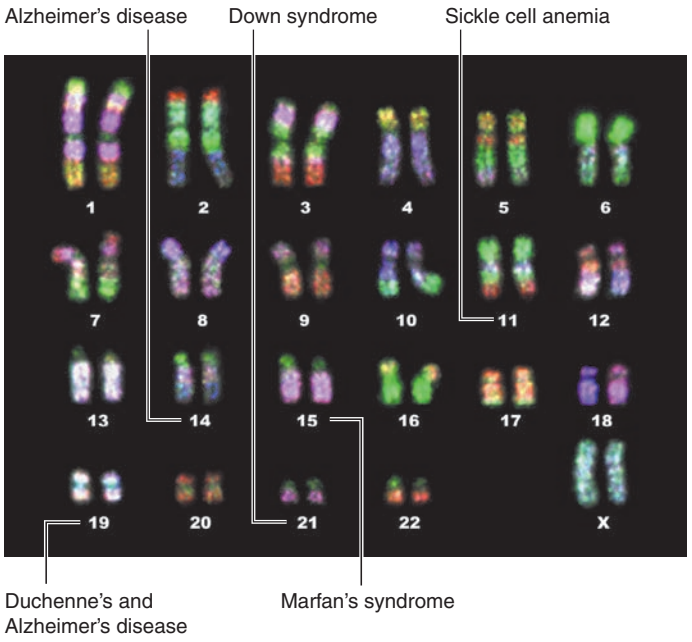
Beyond catching crooks and identifying fathers, genetic technology is also used for more basic purposes. One of the most interesting projects in modern genetics was the sequencing of the entire human **genome**. A genome is the complete set of genes (and alleles) in a certain organism.

genome Total genetic content of an organism.

The Human Genome Project, begun in 1990 and essentially finished in 2003, was a massive research undertaking. This project required numerous new technologies, as the speed of sequencing increased by several orders of magni-

Human karyotype showing selected genetic disorders • Figure 20.18

Based on the information gleaned from the Human Genome Project, many of the genes responsible for congenital diseases have been precisely located. This figure shows the chromosomal locations of just a few of these genes.



tude during the process. After a flurry of invention, fast, simple DNA technologies were introduced and used to expedite the mapping of the human genome. By 2002, **DNA sequencing** and transgenic bacteria production were commonplace enough to be available in many American high school biology labs.

DNA sequencing
Determining the sequence of A, C, T, and G on a gene or chromosome.

The goals of the Human Genome Project included:

- Identifying all the genes in human DNA
- Determining the sequences of the more than 3 billion nitrogenous base pairs in human DNA
- Storing this information in databases
- Improving tools for data analysis
- Transferring related technologies to the private sector
- Addressing the ethical, legal, and social issues that would arise from this knowledge

In completing the map of the human genome, scientists were able to locate the precise chromosome, and even the location on that chromosome, of the genes responsible for many congenital diseases. Some of those are shown in Figure 20.18. Duchenne's muscular dystrophy, Marfan's syndrome, and Alzheimer's disease are among the many diseases we now can identify in the genome. In addition, we can now compare the human genome to that of other organisms, giving us a better understanding of evolutionary relationships. Scientists can trace the history of particular genes through the animal or plant kingdoms, hypothesizing about the meaning of conserved or radically altered genes.

Although the science behind this information is accepted and part of mainstream biology classes, it is quite new. See Table 20.4. Mendel's laws of heredity were first presented in 1865, Beadle and Tatum uncovered gene function in 1941, and in 1953, Watson and Crick proposed the double helix structure of DNA. April 25, 2002, was

DNA discovery: selected events Table 20.4

1865	Mendel's laws of heredity presented.
1868	Miescher isolated "Nuclein," a compound that includes nucleic acid, from pus cells.
1905–1908	Bateson and Punnett showed that genes modify the action of other genes.
1911	Morgan showed genes to be units of inheritance.
1926	Morgan published *Theory of the Gene*.
1939	Belozersky began work showing that DNA and RNA are always present in cells.
1941	Beadle and Tatum discovered gene function.
1944	McClintock found that genes can be transposed from one chromosome position to another.
1953	Watson and Crick proposed a double-stranded, helical, complementary, antiparallel model for DNA.
1966	Nirenberg, Mathaei, and Ochoa demonstrated that the sequence of three nucleotides (a codon) determines each of 20 amino acids.
1973	First human gene-mapping conference held.
1990	Human Genome Project launched.
2000	Working draft of human genome sequence completed.
2003	Sequencing of the human genome completed.
2003	Celebrated 50 years of DNA's double helix.
2005	The Genographic Project announced by National Geographic, IBM, and others.
2007	James D. Watson was the first person to have his full genome sequenced.

Adapted from Access Excellence at the National Health Museum, http://www.accessexcellence.org/RC/AB/BC/Search-for-DNA.html

WILEY PLUS Video

ETHICS AND ISSUES

Can Your Genetic Information Be Used Against You?

Yes, it can.

Is it legal to use your genetic information against you (not including criminal cases)?

No, it is not—at least it will not be in the near future.

On May 21, 2008, President George W. Bush signed into law the Genetic Information Nondiscrimination Act (GINA) of 2008, which prohibits discrimination in the workplace and by health insurers on the basis of an individual's genetic makeup. GINA was nearly 15 years in the making. Since the late 1980s, both scientists and the public have realized that the ability to identify the genetic basis of human disease is a double-edged sword. While allowing for individualized prevention strategies, early detection, and potentially unique treatments, genetic testing also makes it possible for insurers and employers to discriminate against certain individuals.

To date, scientists have determined that as many as 5,000 different diseases have a genetic component. These range from straightforward inherited diseases, such as Huntington's disease or cystic fibrosis, to diseases that involve a genetic predisposition, such as colon cancer or diabetes. People with a genetic predisposition for a particular disease have a higher likelihood of developing that disease than do individuals who lack that gene or genes.

Beginning in the mid-1990s, surveys of Americans uncovered anecdotal information about discrimination by insurance companies and employers. As early as the 1970s, some companies tested African Americans, usually without their knowledge, for the gene associated with sickle cell disease. Responding to numerous complaints about such testing, Louisiana and Florida became the first states to ban discrimination on the basis of genetic tests. Since then, many other states have passed laws barring such discrimination.

Critical Reasoning Issues In 2001, the U.S. Equal Employment Opportunity Commission (EEOC) settled a complaint against the Burlington Northern Santa Fe Railroad for secretly testing employees for a rare genetic condition that causes carpal tunnel syndrome as one of its symptoms. The company said the testing was done to determine whether the high incidence of repetitive-stress injury among its workers was due to working conditions that could be changed or whether it was due to the workers' genetic characteristics. This is another example of the frequency of questions about how much of our behavior is genetically based and how much is caused by environmental factors—questions that are constantly being asked and answered in different ways in different contexts.

Think Critically

1. Can you create a scenario under which it would be legal—and indeed beneficial—for employers to screen potential new hires or current employees for genetic predisposition to disease?
2. If Burlington Northern Santa Fe had found a high incidence of this rare genetic condition among its employees with carpal tunnel syndrome, how should it have responded?
3. Would a national health insurance program make GINA obsolete?

designated the first official **National DNA Day** to commemorate 50 years of DNA research, rather arbitrarily beginning with Watson and Crick's model of the double helix and ending with the completion of the sequence of the human genome. Although not on most calendars, this day is commemorated in the scientific community, and perhaps in your biology class, as a day to reflect on all that we have learned in such a short period.

With rapid knowledge comes the need for ethical debate. What do we do with this information? Should we sequence the genotypes of every individual soon after birth? Should we make the **genetic fingerprint** of each individual as accessible as his or her dermal fingerprint is today? These questions are currently being debated in both the scientific and public communities. See *Ethics and Issues: Can Your Genetic Information Be Used Against You?*

Genetics Helps Us Understand Evolution

DNA is the most fascinating four-letter language in history. As we have seen, it is the basis for our genetic code and the genetic code of all living things. Here's something that may surprise you: About 60% of our genes overlap closely with those in fungi—yes, mushrooms, mildew, and mold. How can this be? The simplest answer is that nature is lazy: Once it finds a solution to a particular problem, it tends to reuse it. By "solution to a problem," we mean one of the metabolic processes, such as making proteins or oxidizing sugars to continue life, a situation that commonly confronts organisms. Once an early form of life solves a problem, the genes that underlie that solution are passed on to descendant organisms.

We also see this "laziness" in DNA itself. All living organisms, and most viruses, house their genetic code in DNA. Once DNA evolved, there was no need for a better system to encode the information that an organism needs, so the DNA system was passed down again and again. Indeed, DNA is so important that early organisms evolved a way to "proofread" it and correct mistakes after cell division. As with other biological solutions, this proofreading mechanism was passed down and is probably active in your cells at this very moment. Chapter 21 introduces evolution at the genetic level, and then takes us up and out of the cellular details to provide a better view of the whole planet and where evolution has led.

CONCEPT CHECK

STOP

1. **What** is the function of a restriction enzyme? **What** information can be obtained through PCR?
2. **What** is genetic modification? **How** is a transgenic organism different from a cloned organism?
3. **How** is RFLP analysis used in criminal cases?
4. **What** are major outcomes of the Human Genome Project?

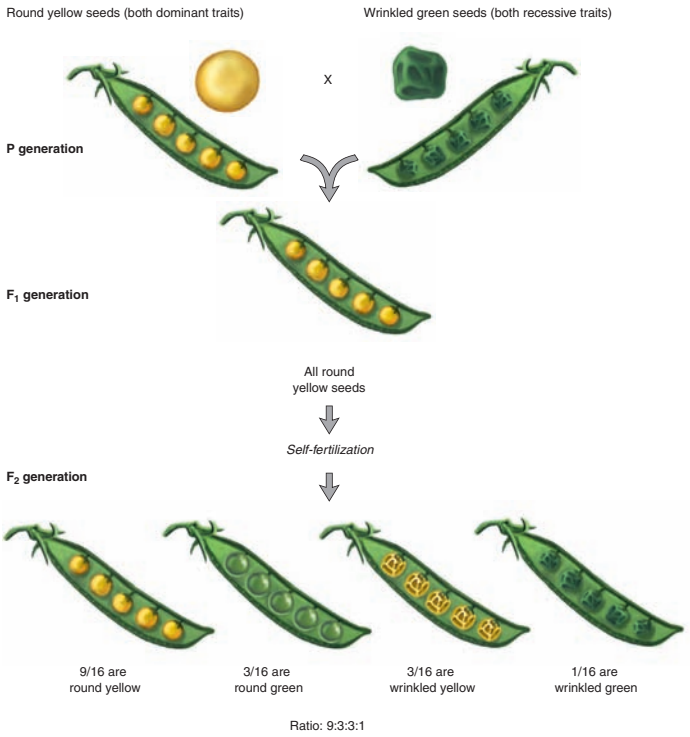
Summary

THE PLANNER

1 Traits Are Inherited in Specific Patterns 556

- Discussing inheritance and genetics requires a set of terms that precisely define genetic characteristics. On the one hand, eggs and sperm carry only half the chromosome number of the entire human, a condition referred to as **haploid**. Mature human cells, on the other hand, have a full set of chromosomes, referred to as **diploid.**
- Working with seven traits in pea plants, shown here, Gregor Mendel explained the predictable relationship between dominant and recessive traits. He also described the laws of segregation and of independent assortment.
- The two kinds of cell division, mitosis and meiosis, are keys to studying genetics.

Figure 20.2



2 Modern Genetics Uncovers a Molecular Picture 562

- **Genotype** is used when discussing the actual genes present on the chromosomes, whereas **phenotype** is used when discussing the outward appearance resulting from the presence of those genes. Alternate forms of a gene are called alleles.
- During meiosis, these alleles separate so each gamete gets one allele instead of the normal pair. At fertilization, maternal and paternal alleles are joined to form the diploid content of the new individual. If both alleles are the same, the individual is homozygous. If the two alleles are different, the individual is heterozygous.
- The vast majority of human traits are codominant, incompletely dominant, polygenic, or **multifactorial**.

3 The Central Dogma: Genes Direct the Formation of Proteins 566

- One gene, one protein—DNA codes for protein formation. Beadle and Tatum proved that DNA is the molecule of inheritance in their benchmark experiment with *Neurospora*. By knocking out genes with radiation and then replacing the products of those nonfunctional genes, these two men demonstrated that DNA and not protein was the molecule of inheritance.

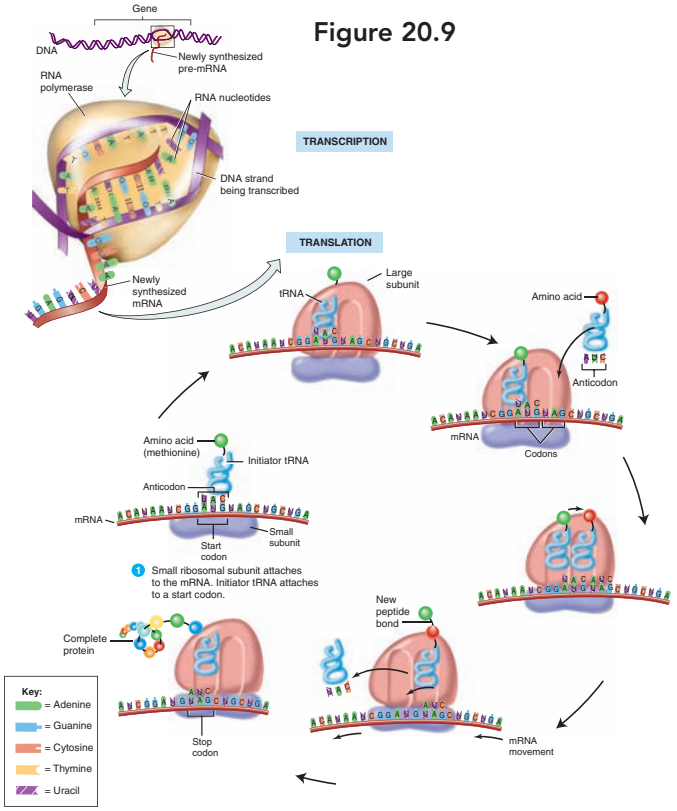


Figure 20.9

- Transcription "reads" nuclear DNA to an mRNA molecule that can leave the nucleus. Translation (see above) of that message in the cytoplasm produces a protein.

4 Genetic Theory Is Put to Practical Use 569

- Sex-linked traits are carried on either the X or the Y chromosome. Because the X chromosome is much larger and seems to include more functional genes, most sex-linked traits are carried on it. Sex-influenced traits are those that are not present on the X or Y chromosome but are more prevalent in one gender. Often, the hormones estrogen and testosterone aggravate or promote these traits.
- Chromosomal disorders can occur during gamete formation. These include gross chromosomal alterations (gain or loss of entire chromosomes), loss or gain of portions of chromosomes, or even smaller alterations in individual genes. Most infants born with **congenital** defects suffer from troubles with one individual gene. Testing is available for prospective parents concerned that they may produce a child with genetic defects.
- Human genes evolve, just like the genes of other organisms.

5 Biotechnology Has Far-Reaching Effects 575

- Understanding DNA has opened up a whole new field: molecular biology, the study and manipulation of DNA. Molecular biology uses nucleic acid hybridization, gel electrophoresis, (seen here) PCR, and RFLP analysis. Physicians can use these techniques to identify the risks of certain cancers.

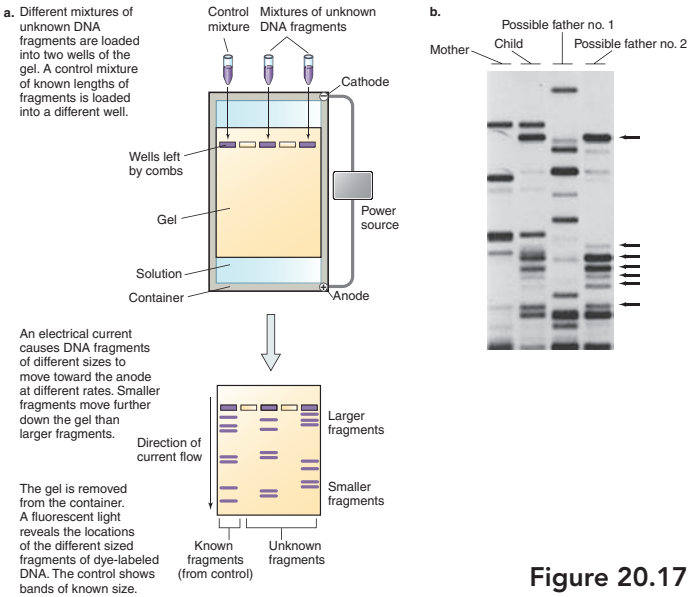


Figure 20.17

- DNA technology has left the classroom and research labs and has become a household word. If your DNA fingerprint (banding pattern) matches a sample found at a crime scene, you had better get a good lawyer.
- As we become more proficient at DNA **splicing** and creating **transgenic** clones, DNA technologies will play an increasingly greater role in our daily lives, but we should be prepared for mistakes along the way.

Key Terms

- agarose 583
- asymptomatic 569
- autosomal 569
- centrifugation 575
- congenital 572
- cross-pollinating 558
- diploid 556
- DNA sequence 556
- DNA sequencing 585
- evolution 571
- fitness 563
- genome 584
- genotype 562
- haploid 556
- homologous 562
- multifactorial disorder 572
- palindrome 570
- phenotype 562
- plasmids 579
- polymerization 578
- recombinant DNA 578
- RNA or DNA primer 582
- self-pollinating 558
- somatic 563
- spliced 578
- transgenic 579

Critical and Creative Thinking Questions

1. Multifactorial traits are influenced by genetics and the environment. These traits, such as height and weight, are expressed in a range of phenotypes in the population. This complication leads to the long-running "nature versus nurture" argument. How could you determine how much the environment affects a particular genetic trait? Design an experiment that would, at least theoretically, shed light on this age-old debate.
2. Transcription and translation are precisely controlled. There is almost no error in the base pairing of nucleotides, ensuring that the DNA code is transcribed reliably. List the steps in transcription and translation in order, and indicate which step(s) can introduce mutations.
3. PCR, DNA transcription, and simple inheritance are all based on the integrity of the DNA base-pairing rules. What are these rules? What enzymes ensure that these rules are not violated? How does this relate to cancer?
4. **CLINICAL CLICK QUESTION**
   Your breakfast cereal claims to be 100% natural, GMO-free. You wish to test this, because you are not a fan of false advertising. Fortunately there is a genetic marker that is carried on all transgenic genes. This marker is used as the starting material for creating a gene in the lab, and is inserted into the transgenic along with the gene. Of course, the marker is found in very small quantities in the final food product, and what little there is may become degraded as the grain is processed into meal for the cereal. If the marker DNA is present, it will be difficult to isolate. What biotechnology will amplify this small amount of DNA m the cereal sample? Once you have successfully amplified any transgenic genes that are in the cereal sample, how will you visualize them? What techniques will you use to identify the presence of this marker gene? With what other samples might you want to compare your possibly GMO-free cereal? For help with this problem, visit http://www.worldfoodscience.org/cmis/?pid=1003869

5. What is a transgenic organism? In your own words, explain the process of creating such an organism. If such an organism is created, we may wish to clone it to get many individuals with the new gene. Is this the same as asexual reproduction? Why or why not?

What is happening in this picture?

Who will buy my papayas? Just a few short decades ago, the answer to that question for many papaya growers in the Hawaiian Islands was "no one." A virus causing ring spot had appeared on these isolated islands and was destroying the papaya crop at an alarming rate. The University of Hawaii researchers went to work, and in the late 1980s discovered that they could genetically modify the papaya plant to promote immunity to the ring spot virus. Transferring genes for the ring spot virus capsid directly into the papaya plant genome created a resistant breed of papaya.

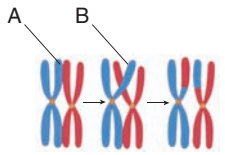
Think Critically

1. Diagram the steps that must be taken to produce the GM papaya plants. What technologies were most likely used to create this virus-surviving cultivar?
2. Since 1999, the GM cultivars have been producing papaya in Hawaii. More than three-quarters of the total papaya crop comes from these plants. How does this affect the local economy? Is this application of GM a good use of biotechnology?
3. Can you tell the difference between GM papayas and non-GM papayas? Why or why not?

Self-Test

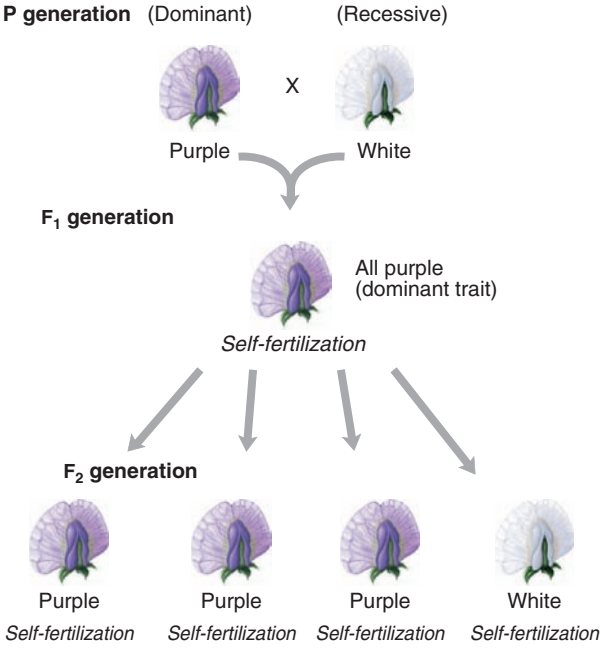
1. The term that describes the appearance of an organism is _____.
   a. genotype
   b. phenotype
   c. DNA sequence

2. The process indicated as B on the figure is important because it _____.
   a. increases the chromosome number in the gametes
   b. increases the genetic combinations of the resulting gametes
   c. organizes the chromosomes before splitting them apart
   d. Two of these answers are correct.



3. Gregor Mendel is known as the father of genetics because ____.
   a. he was the only person looking at genetic variation in the 1800s
   b. his research was thorough and included quantifiable data
   c. he used pea plants when others were using cows and corn
   d. he studied both the F_1 and the F_2 generations

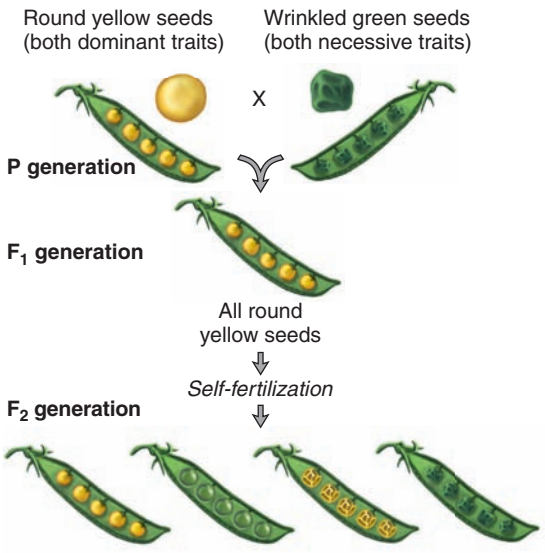
4. In the F_2 generation of his pea plants, Mendel consistently observed a phenotypic ratio of _____. (See the diagram for assistance in answering this question.)
   a. 1:2:1
   b. 3:1
   c. 9:3:3:1
   d. 1:1



5. The law of independent assortment states that the heritable units of parent plants are randomly separated during gamete formation.
   a. True
   b. False

6. As shown in this figure, what is the probability of an individual F_2 pea plant showing both dominant traits in its phenotype?

a. 13/16
b. 9/16
c. 4/16
d. 1/16



7. An individual who expresses the dominant phenotype for an allele must be _____.

a. heterozygous
b. homozygous dominant
c. heterozygous dominant
d. either heterozygous or homozygous dominant

8. Most human traits show a _____ pattern of inheritance.

a. dominant/recessive
b. codominant
c. polygenic
d. multifactorial

9. Beadle and Tatum's experiment can be summarized by the saying, "_____."

a. You are what you eat
b. DNA is the molecule of inheritance
c. Proteins are the molecules of inheritance
d. X-rays cause knock-outs

10. The central dogma of biology states that the process of _____ is relevant to all of biology.

a. meiosis
b. polymerase chain reaction
c. transcription/translation
d. evolution

11. One good reason for undergoing genetic counseling is to determine _____.

a. emotional compatibility
b. your likelihood of contracting a genetic disease
c. the number of mutations in your DNA
d. your likelihood of passing on a deleterious gene to your offspring

12. The process of _____ pulls DNA through a semisolid matrix, separating out pieces of DNA by size.

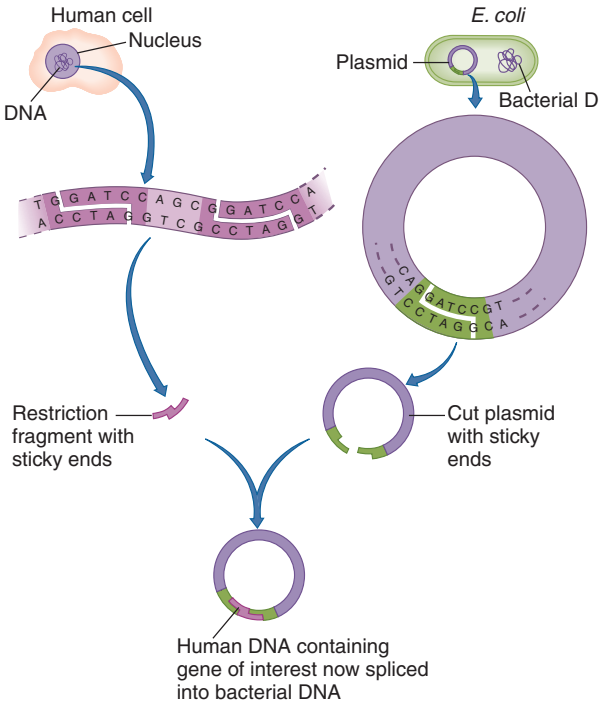
a. nucleic acid hybridization
b. gel electrophoresis
c. polymerase chain reaction (PCR)
d. restriction fragment-length polymorphism (RFLP)

13. _____ is used to produce and compare DNA fingerprints.

a. Nucleic acid hybridization
b. Gel electrophoresis
c. Polymerase chain reaction (PCR)
d. Restriction fragment-length polymorphism (RFLP)

14. The process shown in this figure can be used to _____.

a. prepare samples of DNA for fingerprinting comparisons
b. amplify the amount of DNA in a sample
c. isolate purified DNA
d. create transgenic organisms



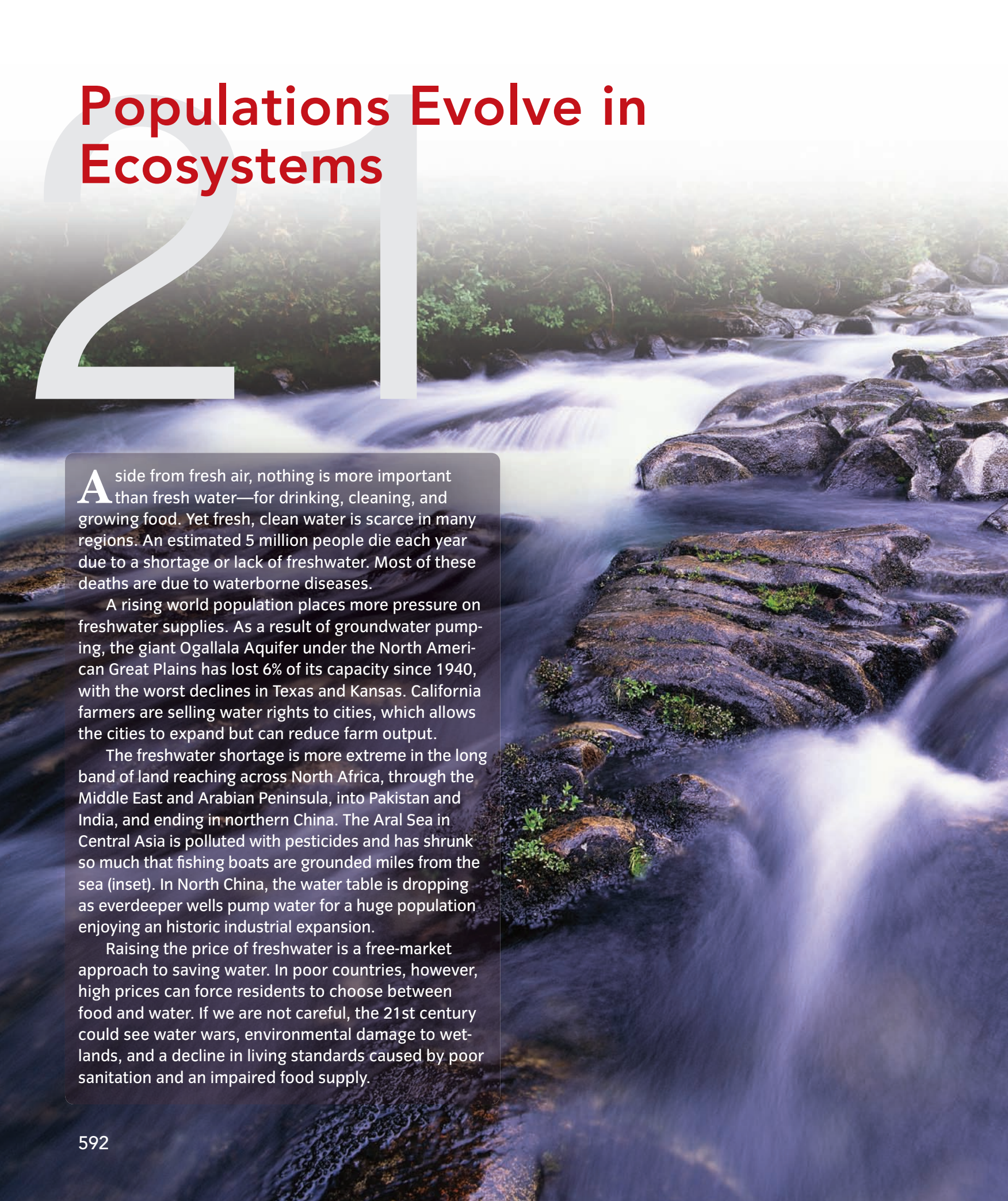
15. The Human Genome Project was undertaken to _____.

a. identify all the genes in human DNA
b. improve tools for both DNA and data analysis
c. address the legal, ethical, and social issues surrounding DNA research
d. All of the above were stated goals of the project.

THE PLANNER

Review your Chapter Planner on the chapter opener and check off your completed work.

21 Populations Evolve in Ecosystems



Aside from fresh air, nothing is more important than fresh water—for drinking, cleaning, and growing food. Yet fresh, clean water is scarce in many regions. An estimated 5 million people die each year due to a shortage or lack of freshwater. Most of these deaths are due to waterborne diseases.

A rising world population places more pressure on freshwater supplies. As a result of groundwater pumping, the giant Ogallala Aquifer under the North American Great Plains has lost 6% of its capacity since 1940, with the worst declines in Texas and Kansas. California farmers are selling water rights to cities, which allows the cities to expand but can reduce farm output.

The freshwater shortage is more extreme in the long band of land reaching across North Africa, through the Middle East and Arabian Peninsula, into Pakistan and India, and ending in northern China. The Aral Sea in Central Asia is polluted with pesticides and has shrunk so much that fishing boats are grounded miles from the sea (inset). In North China, the water table is dropping as everdeeper wells pump water for a huge population enjoying an historic industrial expansion.

Raising the price of freshwater is a free-market approach to saving water. In poor countries, however, high prices can force residents to choose between food and water. If we are not careful, the 21st century could see water wars, environmental damage to wetlands, and a decline in living standards caused by poor sanitation and an impaired food supply.

CHAPTER PLANNER

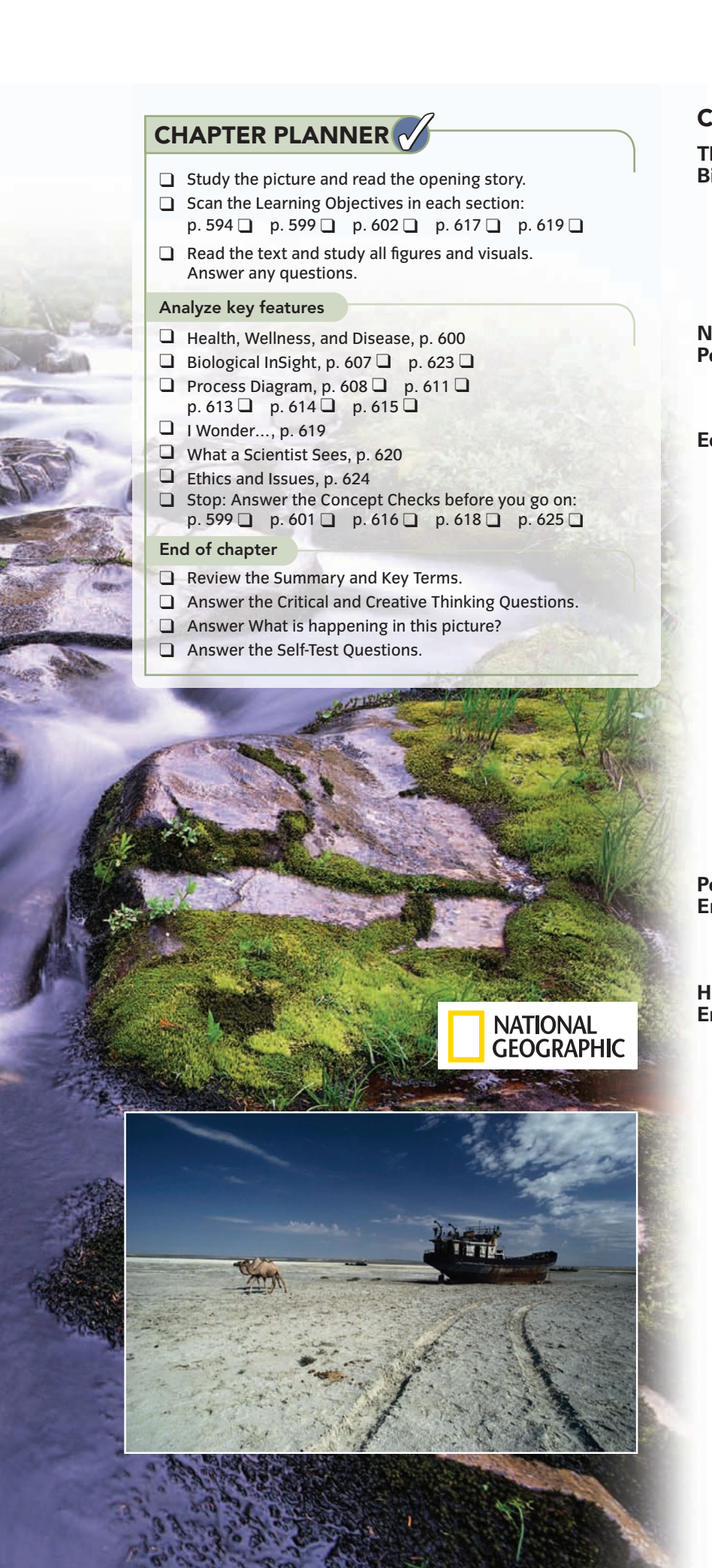
- ❑ Study the picture and read the opening story.
- ❑ Scan the Learning Objectives in each section:
  p. 594 ❑ p. 599 ❑ p. 602 ❑ p. 617 ❑ p. 619 ❑
- ❑ Read the text and study all figures and visuals. Answer any questions.

Analyze key features

- ❑ Health, Wellness, and Disease, p. 600
- ❑ Biological InSight, p. 607 ❑ p. 623 ❑
- ❑ Process Diagram, p. 608 ❑ p. 611 ❑
  p. 613 ❑ p. 614 ❑ p. 615 ❑
- ❑ I Wonder..., p. 619
- ❑ What a Scientist Sees, p. 620
- ❑ Ethics and Issues, p. 624
- ❑ Stop: Answer the Concept Checks before you go on:
  p. 599 ❑ p. 601 ❑ p. 616 ❑ p. 618 ❑ p. 625 ❑

End of chapter

- ❑ Review the Summary and Key Terms.
- ❑ Answer the Critical and Creative Thinking Questions.
- ❑ Answer What is happening in this picture?
- ❑ Answer the Self-Test Questions.



CHAPTER OUTLINE

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- Life on Earth Goes On

21.1 The Theory of Evolution Is the Foundation of Biology

LEARNING OBJECTIVES

1. **Appreciate** the scientific nature of the theory of evolution.
2. **Outline** the history of our current "evolution in the classroom" debate.
3. **Briefly** describe natural selection.
4. **List** the five criteria that would allow a population's gene pool to remain unchanging.
5. **Give** two examples of evolution in action.

Evolution. Even the word can cause an argument. What is evolution? Why does the theory of evolution hold such emotional sway over us, while few nonscientists give a second thought to the cell theory or the atomic theory? Although the theory of gravity is much less understood than the theory of evolution, we don't jump out of a skyscraper window and claim "gravity is just a theory."

Many who loudly criticize the teaching of evolution have serious misconceptions about what it really means. The theory of evolution, as outlined by Charles Darwin in 1859 and refined by thousands of scientists in the intervening century and a half, is an explanation for the appearance, relationships, and distribution of the myriad life-forms on the Earth. Darwin studied life—in the barnyard and the backyard, on islands and volcanoes, in rain forests and deserts—for decades. He attributed the differences in the life-forms he observed to **natural selection**, the advantage that one phenotype may have over another in any given situation or environment.

Interestingly, Darwin was not the only scientist to put forth this notion. Alfred Russel Wallace developed similar views on the origin of species. In 1858, Wallace wrote Darwin outlining a theory of evolution—almost exactly the same theory that Darwin himself had spent decades developing. Wallace and Darwin both presented their ideas and published important works, but we attribute the theory of evolution to Darwin due to his extensive years of research backing his publications.

Curiously, Charles Darwin seldom used the word "evolution" in his epochal book, *On the Origin of Species* (1859). Instead, he preferred "descent with modification," considering it a better description of his ideas. Darwin proposed that natural selection caused the modifications he and other scientists documented. His definition of natural selection rested on four general statements:

1. All organisms produce more offspring than can survive and reproduce in subsequent generations.
2. Organisms show differences that can be inherited.
3. Variations among organisms can increase or decrease each individual's ability to reproduce.
4. Variations that increase the likelihood of successful reproduction will be passed on to future generations.

Darwin recognized that the excessive number of offspring in natural populations caused competition for resources like food and shelter, and that individuals with more ability to acquire these resources would survive and reproduce, so traits that helped the parents survive would be passed to the next generation.

Darwin, like Mendel, made meticulous notes about everything he saw. Unlike Mendel, who was able to stay in his monastery's garden, Darwin went around the world to get his ideas, as shown in **Figure 21.1**.

Evolution Equals Changes in Allele Frequency

As we did with Mendel, we now need to introduce terms that Darwin wouldn't have known to explain our current understanding. Scientists now define evolution more precisely as any change in the frequency of alleles in a population. In every population, genes are encoded in several forms. The frequency of these different forms, the allele frequencies, can be calculated. If those frequencies change, evolution has occurred.

The most common force that changes these allele frequencies is natural selection. Natural selection occurs because an organism's environment may favor one phenotype over another at a given time, so individuals with the "right" phenotype have a greater chance of reaching reproductive age and passing on their "better" genes to the next generation.

Darwin's voyage on the *Beagle* • Figure 21.1

On his voyage around the world, Darwin saw bands of seashells 30 feet above the sea in Cape Verde, near West Africa. How did they get there? He gawked at dinosaur fossils buried in the Earth in Argentina, and he observed similar anatomy in a series of related birds in the Galápagos Islands, off the coast of Ecuador, for which he became famous. By the time he returned home, all the ingredients of his theory were in place: variation, time, competition, change, death, and related groups of species.

The layperson's understanding of natural selection is embodied in the phrase "survival of the fittest." Fitness is the ability of an organism to survive and successfully reproduce, not to run 10 kilometers in under an hour. The key to fitness is to leave more copies of your genes in the next generation. A woman who dies at age 25 but leaves six surviving children is biologically more "fit" than a woman who runs marathons and lives to be 98 but has only two children.

As we saw in Chapter 2, the result of natural selection is **adaptation**, an adjustment or series of adjustments a population or species makes in a given environment over time. Over enough time, these adaptations may result in a new species.

The theory of evolution says nothing about higher powers. The theory of evolution does not include a planned universe, an intelligent designer, or any supernatural or external guiding power of any sort. (Natural selection may properly be thought of as an internal response to external and impartial forces acting on the individual.) Evolution's two strongest antagonistic schools of thought, **creationism** and **intelligent design** or ID, both require the presence of a higher power investing energy in the life-forms on the Earth.

Although some tenets of the theory of natural selection are difficult to test experimentally, leaving questions that scientists have yet to answer, neither of the alternative suggestions is based on the masses of scientific evidence that uphold the theory of Darwin and Wallace. Both alternatives include nonnatural (supernatural)

creationism
Belief in a literal interpretation of the Biblical story of the creation of the universe, the Earth, and life.

intelligent design
The hypothesis that complex biological creatures were designed by intelligent beings rather than simply evolving through natural selection processes.

intervention and therefore cannot be investigated with the scientific method. In fact, they make no testable predictions whatsoever.

Recall that scientific hypotheses must be testable and falsifiable. The overall theory of natural selection is testable despite difficulties in directly testing some of its specifics. Experiments can be designed to show natural selection in action. We see examples all around us: in the rapid change of the HIV virus that can make it resist drugs after repeated exposure, in the appearance of antibiotic-resistant bacteria, and even in the changes in prey species that allow them to avoid being eaten by predators.

The principles of creationism and intelligent design are neither testable nor falsifiable. Although the statement "God created heavens and Earth" may for argument's sake be labeled a hypothesis, it is not one that can be tested, and therefore it is not a *scientific* hypothesis. For this reason, it is incorrect and inappropriate to include such theological or philosophical principles in a science curriculum, except as examples of untestable, and therefore nonscientific, hypotheses.

Individuals Don't Evolve—Populations Do

After many years, and despite our understanding of the molecular processes of evolution, no one has yet found a basic flaw with Darwin's notion of descent with modification. The current picture of evolution is as an unpredictable and natural process of descent over time through genetic modifications. The important phrases in this understanding are "descent over time," "genetic modification," and "unpredictable and natural."

Evolution takes time. Individuals do not evolve; populations evolve. Although Darwin envisioned gradual and subtle changes that would build up over many generations, we now know that changes can also be rapid. In organisms with short life spans, such as bacteria or protozoans, significant changes in allelic frequency can occur within a few decades. Whether it takes eons or merely years, evolution alters the frequency of alleles in a population. These allelic differences show up as phenotypic differences in individuals and may eventually cause enough divergence to create new species over long periods of time. Evolution, therefore, is a change in allele frequency in a population over time.

Small adaptive changes in allele frequency in a population's gene pool are called **microevolution**. The term **macroevolution** is used when a new species is created through these changes in allele frequencies in a population's gene pool, leading to more dramatic changes over longer periods, such as the transformation of a fish into a tetrapod.

microevolution Evolution occurring through a series of small genetic changes, typically referring to changes within populations.

macroevolution Evolution over long periods of time, resulting in vastly different organisms, typically referring to changes leading directly to new species.

The Hardy–Weinberg equation specifies how alleles change. Many factors can contribute to changes in allele frequencies. Independently, the population biologists Godfray Hardy and Wilhelm Weinberg described a list of characteristics in a population that would prevent changes in both the alleles and their frequencies in the gene pool over time. For no evolution to occur, a population must meet these requirements:

1. The population must be extremely large—in fact, effectively infinite—to eliminate the possibility of random **genetic drift**.
2. The individuals must reproduce sexually and mate randomly within the population, meaning that the only criterion for mate selection is gender.
3. No random mutations can occur, a condition that does not occur in the natural world.
4. There is no **selection pressure** on the population.
5. There is no **gene flow** into or out of the population.

genetic drift Random differences in the frequency of an allele within a small or isolated population due to chance events.

selection pressure Any external forces that cause differences in the fitness of individuals having particular alleles.

gene flow Gain or loss of alleles in the gene pool of a population as individuals enter or leave by migration (as opposed to by birth and death).

These criteria are useful for describing an ideal or a benchmark model population, even though such a population does not exist in the real world. We know the frequencies

of alleles do change in natural populations, and therefore evolution is a continuous and ever present process. However, by looking at this list, we can see why evolutionary changes are occurring in that population and get an idea of how quickly they are occurring.

Hardy and Weinberg were not content to generate a list of characteristics for genetic stability; they also saw a need for a mathematical model to predict allele frequencies. The Hardy–Weinberg equilibrium equation is a mathematical representation of the expected genotypic frequencies in a nonevolving population. This equation allows us to compare frequencies of genotypes from one generation to the next, looking for differences between the ideal H-W model population and the actual population. Any difference seen is due to evolution in that population.

The frequencies of two alleles of one gene are designated with the variables p (dominant allele) and q (recessive allele). If there are only two alleles to choose from, the total of the frequencies of p and q must add up to 1. Mathematically, $p + q = 1$. For example, if 32% of the alleles in a population code for a recessive trait, such as attached ear lobes, the other 68% must code for the dominant trait (unattached ear lobes).

As mentioned, those five requirements for a nonevolving population do not occur in the real world. However, the value of the Hardy–Weinberg equation lies in its ability to compare allele frequencies between the model population (which is not evolving) and the natural population (which is most likely evolving) over time. The equation also lets you predict the number of individuals in the **model** population that carry a trait, as seen in **Figure 21.2**. Mathematically, the equation for this prediction is: $p^2 + 2pq + q^2 = 1$. We use the equation to calculate the frequency of homozygous dominant (p^2), heterozygous (pq), and homozygous recessive individuals (q^2). We can compare this calculated frequency for the model population without evolutionary pressure to the natural population's actual allele frequencies. The homozygous recessive phenotype is key to determining the allelic frequencies of p and q in the natural population. A difference between calculated frequencies and observed frequencies indicates that evolution is occurring in the natural population and that at least one of the Hardy–Weinberg criteria is not satisfied.

Let's look at sickle cell anemia, a recessive trait. Homozygous recessive individuals may die young due to their fatal anemia, but they and, more importantly, the heterozygous carriers of the allele are less affected by malaria. In a population where 9% are homozygous recessive (have sickle cell anemia), the Hardy–Weinberg equation can calculate the expected frequency of carriers. Nine percent (0.09) is the value for q^2. Taking the square root finds $q = 0.3$. Since $p + q = 1$, then $p = 1 - q$, or $1 - 0.3$, or 0.7. Knowing the frequency of each allele, you can easily calculate the frequency of heterozygous individuals: $2pq = 2(0.7)(0.3) = 0.42$. Forty-two percent of the population are expected to be sickle cell anemia carriers and therefore partly protected from malaria. This situation is unlikely to be the case in a real population, even in a nonmalarial area, due to other selection pressures.

Evolution Does Not Have an End Goal

Despite the fact that the Hardy–Weinberg equation can help us analyze the course of evolution, keep in mind that evolution is neither linear nor directed. One of the largest misconceptions about evolution is that it is progressive or has an end goal—that it is aiming toward a perfect life-form. Evolution

Hardy–Weinberg equation • Figure 21.2

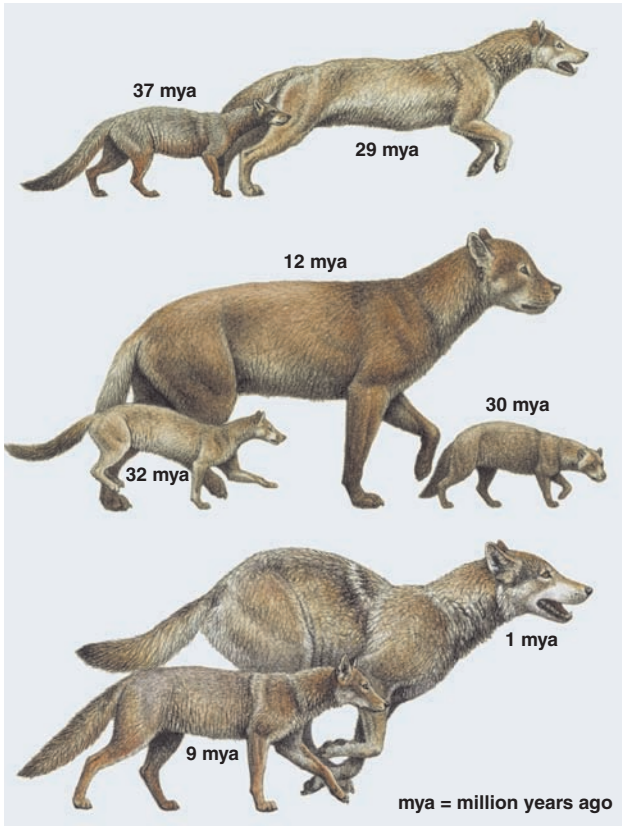
One way to think of the Hardy–Weinberg equation is as a Punnett square for populations, not individuals. If a population has allele A occurring with a frequency of p and an allele a occurring with a frequency of q, this Punnett square is shown. This formula is used to determine the extent of allelic frequency changes that are occurring in a natural population. p = the dominant allele, and q = the recessive allele. Some deviation from predicted frequencies is expected, because the conditions for a nonevolving population are impossible to obtain here on the Earth.

	Allele A, appearing with frequency *p*	**Allele a, appearing with frequency *q***
Allele A, appearing with frequency *p*	AA, with frequency *pp* (*p* squared)	Aa, with frequency *pq*
Allele a, appearing with frequency *q*	aA, with frequency *qp* (equivalent to *pq*)	aa, with frequency *qq* (*q* squared)

$$p^2 + 2pq + q^2 = 1$$

The evolution of wolves • Figure 21.3

The descent with modification of our present-day wolves is depicted here. As the environmental conditions of the Earth changed, different characteristics became helpful in survival. These changes in allele frequency led to great changes in wolf form and function over long periods of time.



is a natural process, and it has no more purpose than gravity. However, evolution can, but does not always, maximize the **fitness** of a population. Allele frequency changes that persist in a population allow the population to exploit the available resources more effectively than other organisms. Sometimes these changes form a new species, and the old one dies off, in a linear alteration. Another possibility is that similar modifications may lead to the formation of two or more **divergent** species. **Figure 21.3** shows one example of descent with modification.

fitness The relative ability of an individual to produce viable (living) offspring that survive to reproduce.

divergent Separating from a common point; growing farther apart.

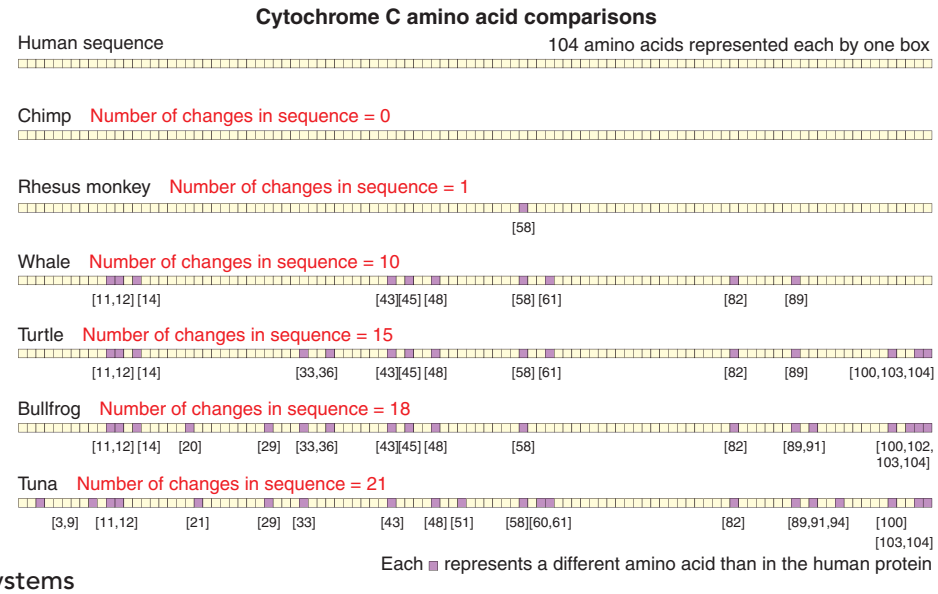
Allele changes can also lead to neutral modifications, because some mutations or mistakes in copying DNA during mitosis have little or no effect on phenotype. These neutral modifications are neither beneficial nor detrimental. However, as environmental conditions change, their significance may change as well. The fitness of any trait is affected by chance events, natural selection, alterations in the environment caused by humans, and natural changes to the environment.

Biochemistry Provides Proof that Evolution Is in the Genes

Recent technical breakthroughs have provided even more support for the theory of evolution. The structures of both proteins and DNA are biochemical evidence for evolutionary relationships. Closely related species have nearly identical DNA sequences; as the relationships become more distant, we see fewer matching sequences. As species develop separately, mutations build up in the DNA. The longer the two species have been separated, the more mutations will have occurred and the more differences there will be in the DNA. These differences will translate into different amino acid sequences in the resulting proteins. See **Figure 21.4** for an evolutionary comparison of one such protein.

DNA sequencing gel • Figure 21.4

This chart compares the amino acid sequence of a common protein, cytochrome c, among many different animals. Each amino acid change indicates a mutation in the DNA that codes for cytochrome c. If you assume that cytochrome c has been used in cellular respiration for millions of years, it logically follows that the more differences you encounter between the cytochrome c sequence of two animals, the more distantly related those two animals are. Verifying this, there are virtually no differences between the amino acid sequence of humans and chimpanzees. We are closely related. Conversely, there are 21 amino acid differences between the sequences of cytochrome c in humans and the tuna. Here is further evidence that we are more distantly related to the tuna than we are to the chimpanzee.



For example, humans and chimpanzees shared a common ancestor about 4 million years ago. Since that time, our DNA and the chimpanzee DNA have mutated and accumulated differences. Cornell University scientists, who were looking for the genes that had changed the most as humans and chimpanzees evolved into their present forms, have recently cataloged these differences. Surprisingly, they discovered the largest differences in genes on the X chromosome and genes associated with the immune system. These areas showed a much faster rate of mutation and therefore much more evolution than, for example, genes that code for proteins expressed in the brain. This finding was surprising, as the biggest evolutionary difference between humans and chimpanzees seems to be the composition or functioning of our brains.

Protein sequences also show the distance between species. Hemoglobin is a common protein that differs only slightly among vertebrate organisms. As with DNA sequences, the degree of variability between hemoglobin sequences suggests the length of reproductive isolation between two species. Our hemoglobin and that of a common grass frog differ by 67 of the 147 amino acids. In dogs, the same protein differs from ours by 32 amino acids, and in macaque monkeys our hemoglobin matches in all but 8 amino acids.

CONCEPT CHECK 

1. **How** do evolution and intelligent design differ?
2. **What** is the history of the theory of evolution?
3. **What** are the four general statements of natural selection?
4. **What** are five criteria that would allow a population's gene pool to remain unchanging?
5. **What** are two examples of evolution in action?

21.2 Natural Selection Has Far-Reaching Effects on Populations

LEARNING OBJECTIVES

1. **Define** fitness in evolutionary terms.
2. **Explain** how the bottleneck effect, the founder effect, and adaptive radiation affect allele frequency.

One of the Hardy–Weinberg criteria for a nonevolving population is the lack of natural selection. Natural selection refers to many forces acting on populations, such as the need to react to climate, the formation of new mutations, and inter- and intraspecific competition for limited resources. The result of natural selection is successful reproduction of only the best-adapted organisms. This selective pressure is the backbone of Darwin's theory of descent with modification and is ever present in nature.

Fitness Is Determined by Natural Selection

The raw materials for natural selection are the random mutations that occur in DNA and the different genetic combinations resulting from sexual reproduction. Mutations occur in nonessential, even unused portions of the DNA over time, as well as in the genes that determine the organism's phenotype. These altered alleles can persist for generations, with little or no detrimental effect. An accumulation of these random mutations over millions of years may be enough to produce new species, assuming that selective pressures change to benefit individuals with the mutations.

When the environment changes, different pressures are put on the resident life-forms. These new pressures may require a different foraging strategy, faster reproduction, or perhaps a faster running speed. Mutations may produce phenotypic variations that are beneficial in a changing environment, conferring an advantage to those

organisms carrying the mutation. If these organisms reproduce, the mutations may pass to future generations, eventually becoming more common in the population.

For example, as wolves prey on deer, the average speed of the deer population increases. The fastest individuals can escape the wolves, while the slower ones get eaten. Those deer that outrun the wolves breed and pass on the alleles for larger muscles, faster muscle contraction, or more efficient joints, which produces faster offspring. Natural selection causes individuals with the combination of traits most suited to the environment to reproduce and leave a larger proportion of their offspring in the next generation. This is the definition of fitness! Assuming that this also holds true for humans, the question in human biology becomes: Do civilizations rise and fall due to environmental changes? If so, we may experience large-scale changes in human populations as the planet continues to warm and CO_2 levels continue to rise. See *Health, Wellness, and Disease: Does Climate Affect Evolutionary Rate?* to investigate this further.

HEALTH, WELLNESS, AND DISEASE

Does Climate Affect Evolutionary Rate?

THE PLANNER

As global temperatures creep upward, scientists wonder what effect this will have on the biology of the planet. One of the more dire predictions is wide-scale extinction of life-forms. Will we find that as our planet's temperature rises, the rate of evolution will keep pace? Dr. Len Gillman from Auckland University of Technology published a paper in the Proceedings of the Royal Society B in June 2009 that provided direct evidence that DNA undergoes point mutations faster in warmer climates than in cooler ones. The team compared the DNA of 130 pairs of mammals found in different latitudes or elevations. These researches looked at only the gene that codes for cytochrome b. This is a ubiquitous protein in the electron transport chain of cellular respiration. They compared the DNA sequence for this gene to a predetermined cytochrome b control gene. Counting the base-pair differences between the test animal's gene and the control gene, the team was able to see which DNA had undergone more mutations. A high number of base-pair substitutions between the test animal's DNA and the control gene indicated a faster mutation rate. Dr. Gillman found that species in warmer climates evolved a full 1.5 times faster than their counterparts in cooler climates. He hypothesized that this was due to the lower metabolic rate of animals in colder temperatures. Animals in colder environments reduce their metabolic activity to conserve energy, while those in warmer climates increase their cellular activity, which in turn causes more divisions in the germ cells (those undergoing meiosis). These results may help explain why the tropics contain such biodiversity, and it may also shed some light on the fate of animals in our evolving climate.

NATIONAL GEOGRAPHIC

Bottleneck effect • Figure 21.5

The 7.9 magnitude Sichuan earthquake in 2008 destroyed many communities, and the aftershocks were deadly as well. Disease and hunger continued to claim many lives after the earthquake ended. The quake was felt as far away as Russia and Japan.

Populations Lose Alleles

Stable populations can be devastated by natural events, such as tsunami or fire. These catastrophes upset whole environments and promote evolution without regard to fitness. In other words, those individuals in the path of the disaster die, regardless of their genetic makeup. When a large portion of any population is suddenly removed, the frequency of alleles in the remaining population may not be representative of the original population. This is the **bottleneck effect**.

Among humans, we witness the bottleneck effect after ecological disasters. The earthquake in the Sichuan province of China on May 12, 2008, killed more than 69,000 villagers without regard to age, gender, or health. Figure 21.5 shows some of the devastation. Fewer individuals from the original populations are left to repopulate their villages. If there is little immigration, the alleles among the remaining individuals will be all that are available for the next generations. If these alleles occur in a different proportion than that found in the original population, a bottleneck has occurred and the gene pool is different than it would have been without the earthquake.

Gene flow can also create new allele frequencies and sometimes even new species. Gene flow mixes genes from different populations when individuals migrate between populations. When individuals leave one population (**emigration**) and join another (**immigration**), they are subtracting alleles from one gene pool and adding to the next. Gene flow may affect allele frequencies by delivering new genetic combinations or removing deleterious ones.

CONCEPT CHECK STOP

1. **Which** is more fit in evolutionary terms, a woman of 98 with two grown children, a female marathon runner with three adopted children, or an overweight mother of five? Defend your answer.
2. **How** does the bottleneck effect affect allele frequency?

21.3 Ecosystems Sustain Life

LEARNING OBJECTIVES

1. **Define** habitat, niche, ecosystem, population, and community.
2. **List** and describe the major biomes.
3. **Summarize** the changes communities go through as they mature.
4. **Describe** a typical food web.
5. **Compare** the water cycle to the nitrogen and phosphorus cycles.
6. **Explain** the importance of the carbon cycle.

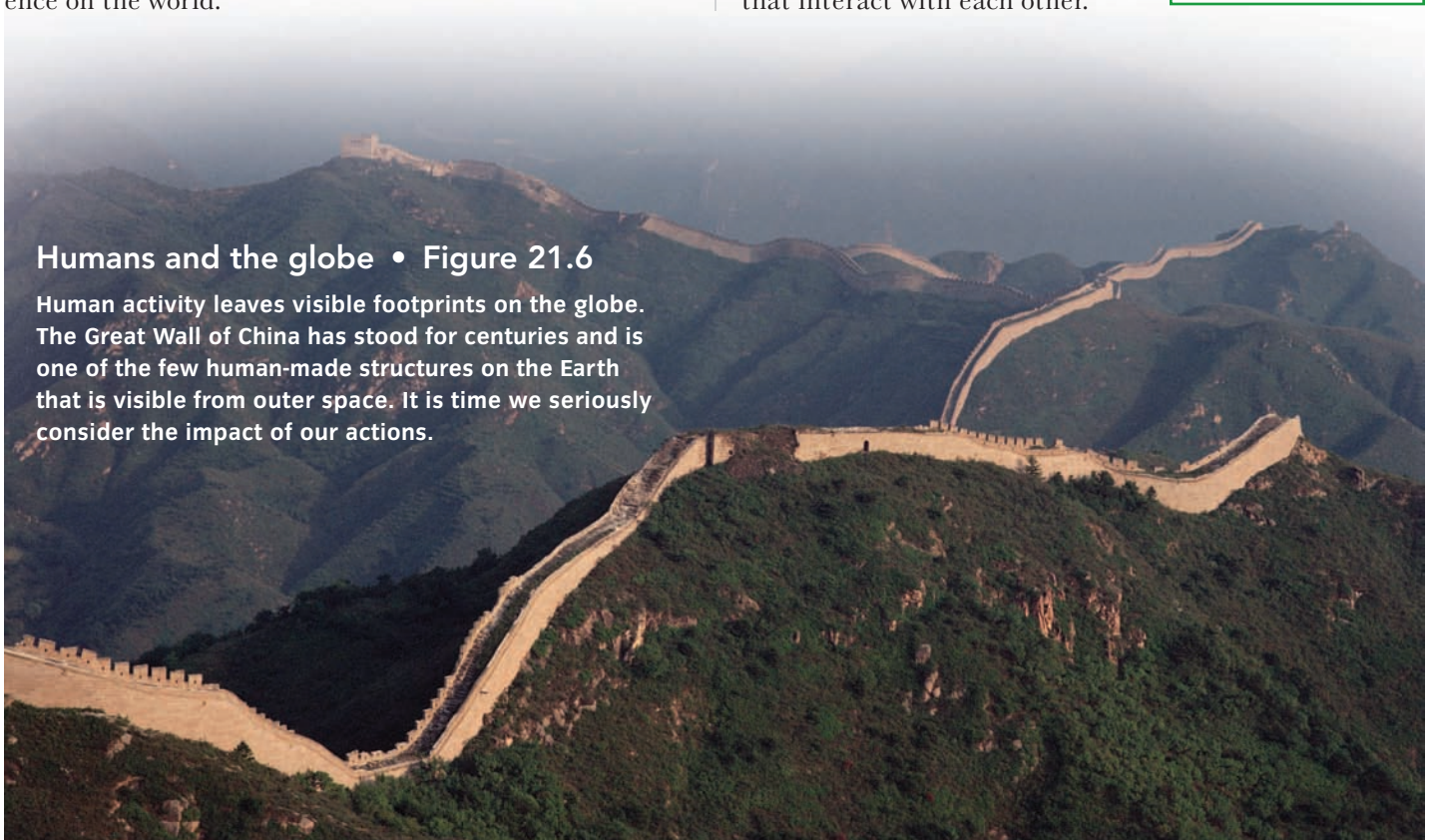
Throughout most of this book, you have been examining the inner workings of an individual. One thing that should be abundantly clear by now is that in biology, nothing happens in isolation. Every muscle contraction, every chemical reaction, every breath you take, affects your entire body. In addition, your entire body is affected by signals from your environment.

As we saw in Chapter 2, the intricate interplay of energy and molecules within your body has parallels in our exterior environment. Water moves through the environment in a predictable pattern, much as it moves through your body. Energy is harvested in the environment and used to create and power organisms just as your body harvests and uses energy to create proteins and power activities. Does the entire North American continent, or even the entire Earth, need to maintain a similar homeostatic balance? How do we as humans fit into the larger world picture? Figure 21.6 shows one example of human influence on the world.

The land, water, and air of the Earth, with life in all its varied forms, comprise our **biosphere**. As we have seen, within this biosphere are smaller interrelated units called **ecosystems**. The field of **ecology** attempts to interpret and explain the interactions between the biotic (living) and abiotic (nonliving) components of ecosystems. The teeming, diverse life-forms that exist all around us are part of our ecosystem. We interact with these organisms and the physical environment, sharing the resources and hazards of the area.

Because scientists prefer order to chaos, there are specific terms for groups of organisms. We will discuss the most common organizational terms in ecology, in order of size. Individuals of the same species occur in **populations**. Populations, in turn, are organized into **communities**, which include more than one species. An ecosystem includes the community or communities interacting with their environment. A **biome** is a group of ecosystems that interact with each other.

biome A regional community characterized by its dominant plant life and climate.



Humans and the globe • Figure 21.6

Human activity leaves visible footprints on the globe. The Great Wall of China has stood for centuries and is one of the few human-made structures on the Earth that is visible from outer space. It is time we seriously consider the impact of our actions.

Relationship between biosphere, ecosystem, community, population, and individual • Figure 21.7

Individual organisms interact in populations. All the reef populations taken together comprise the reef community. When you include the sandy ocean bottom and the water column along with the organisms, you are discussing the reef ecosystem. The entire marine ecosystem is a part of the biosphere.

Populations Can Interbreed

Communities are made up of different **populations**. A population includes all the members of one species living in the same area. All members of a population can interbreed and produce living offspring. The people living and working in midtown Manhattan are a single population within the community. When communities are discussed, only the populations living together are considered. In this instance, the community would be composed of all living organisms in midtown Manhattan. If the physical environment is included, the discussion returns to ecosystems, one of which is seen in Figure 21.7. It is difficult to talk only of communities, because the physical environment plays such a large role in determining which populations are able to survive.

Communities Are Groups of Populations Interacting with One Another

Within ecosystems are communities—groups of organisms interacting with one another, living in the same area, and surviving under the same physical conditions. In New York City, for example, there are as many as 59 distinct communities. One such community includes the plants, animals, and people that live and interact in midtown Manhattan, bordering Central Park. The community of this area consists of the grasses and plants of Central Park, along with the people who live and work around the park. Their pets, pests, and indigenous animals are also part of this community, including dogs, cats, various insects, birds, and rodents. Each of these organisms interacts with the others, living in close proximity under the same or extremely similar conditions.

Biomes Are Groups of Ecosystems Interacting with One Another

In an effort to describe large-scale ecological situations, ecologists have defined nine terrestrial and two aquatic **biomes**, including alpine, temperate, and tropical forests; tundra; grassland; chaparral; desert; and savanna. Also, aquatic biomes can be marine or freshwater. The characteristics of the main terrestrial biomes are listed in Table 21.1 on the following page.

Ecological Succession Can Be Predicted

One amazing thing about communities is their fluidity. We interact with other populations in our community daily; therefore, we are not often aware of subtle changes. Natural communities undergo constant change, with the **dominant population** shifting with conditions. This sequential change in species dominance is called **succession**. We could observe succession in a lawn in a humid region if we suddenly quit caring for it. The "weeds" we constantly fight in a manicured

dominant population The population with the largest number of individuals in an area.

Biomes of the world Table 21.1

	Boreal forest/Alpine	Temperate forest	Tropical forest	Tundra	Grasslands
					
Location	Northern Hemisphere between latitudes 50°and 60°N	Eastern North America, northeastern Asia, Western and Central Europe	Near the Equator between latitudes 23.5°N and 23.5°S	55° to 70° N	Middle latitudes, in the interiors of continents
Temperature	Very low	−30° to 30°C	Varies little between 20° and 25°C	Ice covered; 5°–6°C	−40° to 21°C
Annual precipitation	400 to 1000 mm	750 to 1500 mm	May exceed 2000 mm	150 to 250 mm (usually snow)	250 to 1500 mm
Soil type	Deficient in nutrients, thin and acidic	Fertile and enriched with decaying litter	Deficient in nutrients and acidic	Permafrost	Thin and dry, rich
Dominant flora	Evergreen conifers, such as jack pine, balsam fir, and black spruce	Broad-leaved species, such as oak, hickory, beech, hemlock, maple, elm, and willow	Trees reach 25 to 35 m while plants include orchids, bromeliads, vines, ferns, mosses, and palms	Shrubs, sedges, mosses, lichens, and grasses, flowers	Buffalo grass, sunflower, crazy weed, asters, blazing stars, coneflowers, goldenrods, clover, and wild indigos
Dominant fauna	Woodpeckers, hawks, woodland caribou, bears, weasels, lynxes, foxes, wolves, deer, hares, chipmunks, and shrews	Squirrels, rabbits, skunks, birds, deer, mountain lions, bobcats, timber wolves, and foxes	Birds, bats, small mammals, and insects	Caribou, musk ox, polar bear, shrews, hares, rodents, wolves, foxes, bears, and deer	Coyotes, eagles, bobcats, the gray wolf, wild turkey, flycatcher, Canada geese, crickets, dungbeetle, bison, and prairie chicken

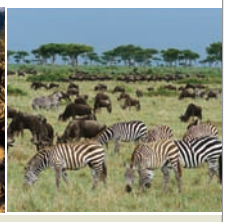
lawn would outcompete the grass for the sunlight, take over the yard, and choke out slower growing plants. Insects that pollinate the weeds would move in, altering the dominant insect species. The weeds would slowly be replaced by shrubs or trees, which are slower growing but able to reach above the weeds and catch more sunlight. Birds and other insect predators would move into the shrubs. The shrubs may eventually be outcompeted by trees. Larger mammals that can live beneath the trees would infiltrate the area. Slow-growing hardwood trees would finally appear, eventually turning the yard into a forest.

Primary and Secondary Succession Occur as Populations Change

The life-forms that appear during succession are more or less predictable for each ecosystem or niche. When an area begins with bare rock or sand, we call the process **primary succession**. Primary succession may occur on any new land, such as fresh lava, beaches, river deltas, or areas recently gouged by glaciers. The **pioneer species** hold the newly formed soil and add to it as they drop organic material, allowing grasses and then larger plants to take over. As the dominant populations change, the process of succession occurs.

pioneer species
The first plant species to colonize a newly established area.

Disasters can restart succession. **Secondary succession** occurs when a disturbance has disrupted a stable ecosystem of plants and animals. Organisms associated with one of the earlier stages of succession again become dominant, so the process of succession starts anew. The land is not newly formed, but the organisms inhabit-

	Chaparral	Desert	Savanna
			
	West coast of the United States, the west coast of South America, Cape Town area of South Africa, western tip of Australia, and coastal areas of Mediterranean	Hot and dry deserts are near the Tropic of Cancer or the Tropic of Capricorn, cold deserts in polar regions	Wide band on either side of the Equator on the edges of tropical forests
	10°–40°C	20 to 49°C; 2 to 26°C	Averages 21°C
	350 to 600 mm annually	150 to 270 mm	100 mm in dry season, 600 mm in wet season
	Rocky, sandy, gravelly, or heavy soils	Sand, exposed bed rock, thin deficient soil	Varies; rocky and sandy to thin to rich
	Poison oak, scrub oak, yucca whipplei, and other shrubs, trees, and cacti	Turpentine bush, prickly pears, brittle bush, sagebrush	Short twisted trees, grasses, plants specialized for nutrient storage
	Coyotes, jack rabbits, mule deer, alligator lizards, horned toads, praying mantis, honeybees, and ladybugs	Small nocturnal carnivores, burrowers, mourning wheatears, horned vipers, antelope, ground squirrels, jackrabbits, and kangaroo rats	Lions, zebras, elephants, giraffes, herds of ungulates, capybara and marshdeer, birds of prey

ing it are again the pioneer species. A graphic example of secondary succession occurred after the Mount St. Helens volcano erupted. The stable community living along the slopes of the mountain was destroyed, causing the return of the pioneer species, as seen in **Figure 21.8**. Leaving your yard to its own devices would be a less dramatic example of secondary succession, as the plants slowly returned to the original community that was there before your house was built.

climax community Relatively stable, mature community that has reached equilibrium after passing through a series of established steps.

Climax communities are stable. When scientists first noticed this progression of communities, they supposed that there was a predictable and stable end to the succession. They looked for **climax communities** and predicted that they would be similar in similar locations. In the dry parts of the U.S. Great Plains, for example, the climax community is prairie. In the same

Secondary succession on the slopes of Mt. St. Helens • Figure 21.8

On May 18, 1980, Mt. St. Helens erupted in an enormous searing blast, sending some 400 million tons of volcanic rock and ash miles into the air and destroying most living things on the slopes of the mountain. However, ecosystems in the blast zones began to establish themselves within a surprisingly short time—even a few months—as pioneer species returned. Secondary succession occurs on soil that is already established, so successional stages appear much more quickly than in primary succession. Even so, many ecologists were surprised by how resilient the mountain's ecosystems seemed to be.

latitudes along the Atlantic coast, however, the climax community is deciduous forest.

Climax communities are less predictable than once assumed, because they reflect the interplay of many factors, including biota, soil, and weather, not just the vegetation. They are, however, stable communities that do not change appreciably in dominant species over many years.

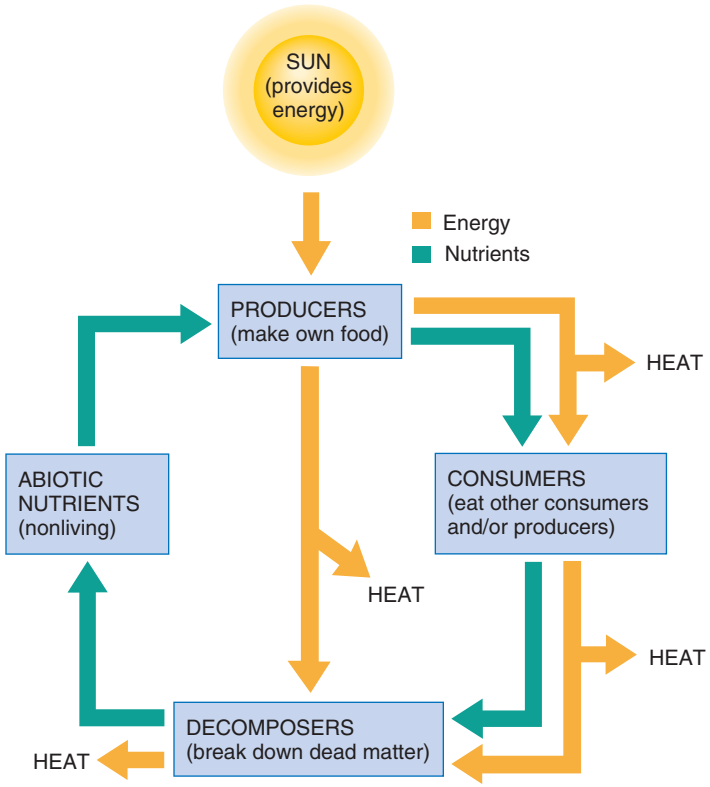
Energy Flows Through an Ecosystem, While Chemicals Cycle

Ecology is all about flow. When studying the interactions of the biotic and abiotic factors in the biosphere, we use the repeated appearance of two factors: energy and fundamental chemicals. **Energy** flows through ecosystems on a one-way trajectory, while many chemicals cycle repeatedly through the biosphere, as outlined in Figure 21.9.

energy Usable heat or power.

Energy flow and resource cycling • Figure 21.9

In this image, energy from the sun travels through the producers, consumers, and decomposers, escaping the system as heat at each step. In contrast, the nutrients cycle through the organisms and abiotic segments of the biosphere.



Energy is supplied by the sun. Energy is constantly supplied to the ecosystem by the sun. **Producers** pick up that energy and use it to convert chemicals to useful organic compounds, which often cycle repeatedly through the biosphere. As **consumers** eat producers, both the energy and chemicals are transferred to the next organism in line. Energy continues to move through the ecosystem until it is lost as heat to the atmosphere. Some of that heat is generated by metabolic activity. Ecosystems need a constant supply of energy to compensate for this heat loss.

producers Organisms that create their own organic compound nutrients from inorganic substances and light; mainly green plants.

consumers Organisms that must ingest organic compounds as nutrients because they cannot manufacture their own.

Chemicals cycle. Chemicals, unlike energy, cycle through organisms and the abiotic portion of the biosphere. The original inorganic compounds used by producers are often made available to other organisms through decomposers and other natural activities. Some chemicals leave the biosphere as they become trapped in geologic sediments, but they return to the biosphere later when resulting rock is broken down.

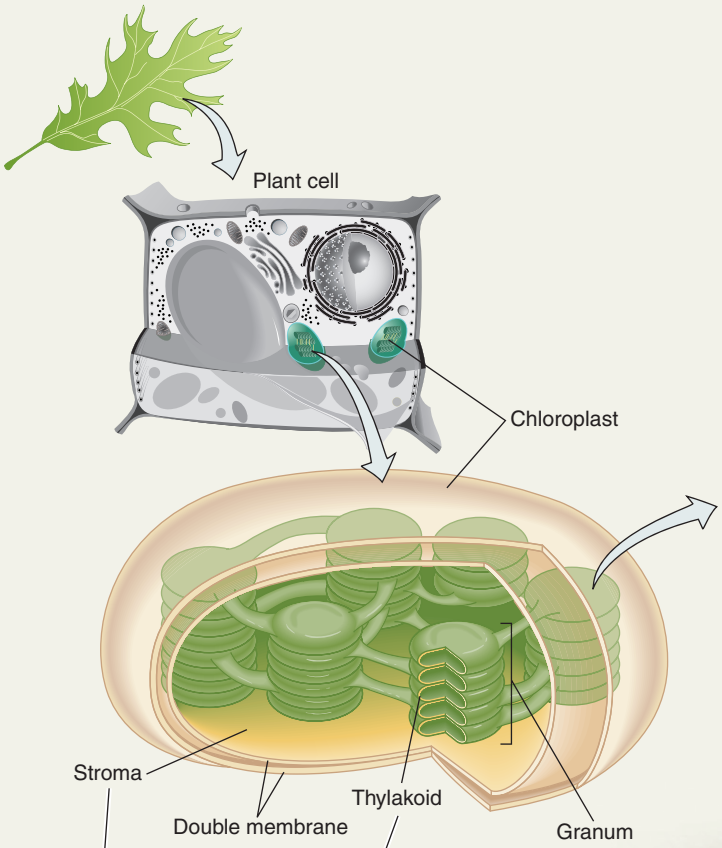
Photosynthesis converts solar energy into chemicals. Energy is harvested by green plants using a **photopigment** called **chlorophyll**, which is usually found in small green organelles called **chloroplasts**. Photosynthesis occurs in these chloroplasts in two stages—the **light reaction** and the **dark reaction,** all of which are represented in Figure 21.10.

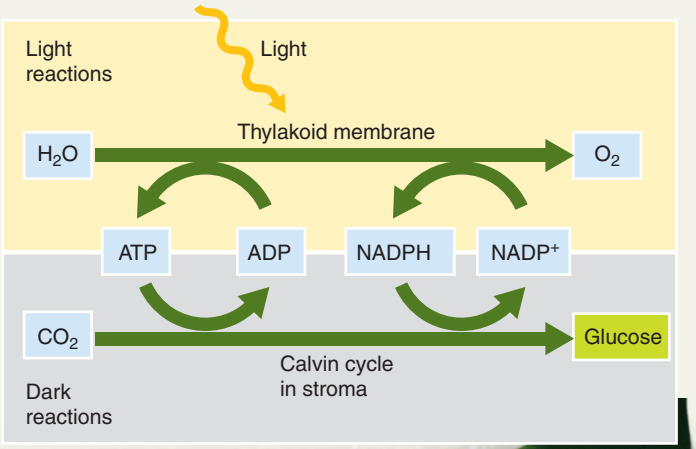
photopigment An organic compound that changes in response to light.

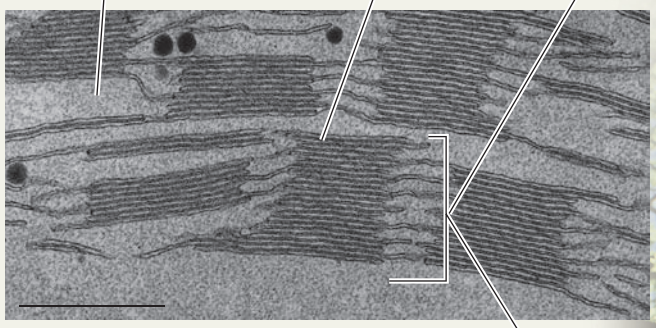
chlorophyll A blue-green photopigment found in plants and algae.

In the light reaction, chlorophyll absorbs a photon of light and releases an excited (energy-carrying) electron. This excited electron is captured by a specialized protein and transferred through a series of compounds, releasing its energy in a slow, controlled fashion. The released energy is collected in ATP and another high-energy compound, **NADPH**. This phase of photosynthesis is called the light reaction because it begins when light is absorbed.

Photosynthesis is a driving force in much of our environment: It converts water and carbon dioxide into oxygen and glucose, using solar power. Many—if not most—species breathe that oxygen and consume those carbohydrates. The chloroplast is the organelle that houses the process of photosynthesis. The light and dark reactions within the chloroplast convert the environment's water and carbon dioxide into oxygen and carbohydrates, fueling much of nature. The umbrella tree shown is in Hanging Rock State Park, North Carolina.







TEM Bar = 0.5 μm Chloroplast grana

NATIONAL GEOGRAPHIC

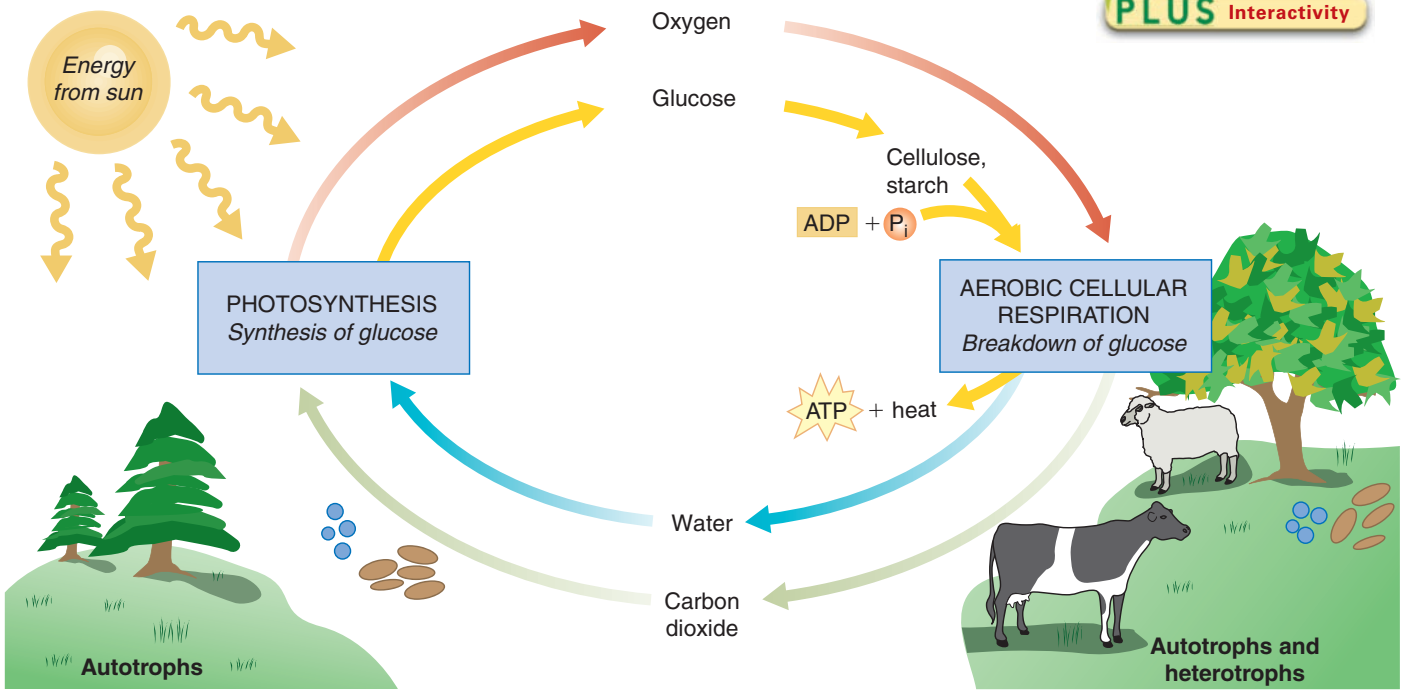
PROCESS DIAGRAM

Photosynthesis/Respiration • Figure 21.11

THE PLANNER

The processes of photosynthesis and respiration are interrelated.

WILEY PLUS Interactivity



The electrons that popped off the chlorophyll molecule during the light reaction must be replaced for the pigment to continue absorbing light. To accomplish this, water is **hydrolyzed**. As the water molecule splits, it replaces the missing electron and releases an oxygen atom to the atmosphere. This oxygen is critical to animal life. Green plants supply the atmosphere with the oxygen needed to sustain the metabolic reactions of respiration in plants and animals.

hydrolyzed
Undergoes process of splitting a water molecule, releasing H^+ and OH^-.

The dark reaction, or **Calvin cycle**, of photosynthesis occurs in the chloroplasts without needing photons. During the Calvin cycle, energy stored in ATP and NADPH is used to convert carbon dioxide into glucose molecules. Because no photons are absorbed, the Calvin cycle can occur day or night.

Once the photosynthetic cycle is completed, plants can use the energy in the newly created glucose for cellular respiration. Plants burn glucose and therefore respire just like animals. They need to produce structural and functional proteins, build the support and storage carbohydrates cellulose and starch, and create the lipids needed for survival. Excess glucose in the plant body can be stored as starch. Each year, green plants produce an estimated 145 billion tons of carbohydrates, equal to about 23 tons per person.

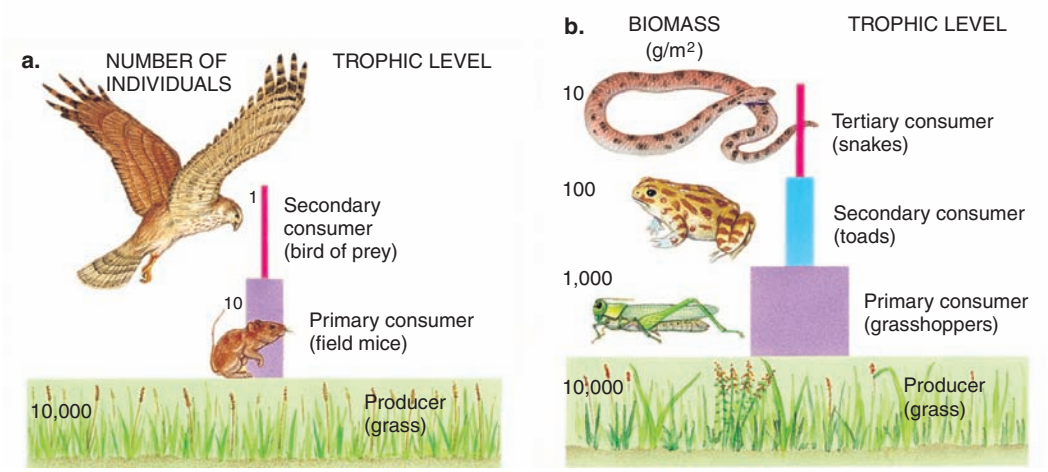
Photosynthesis is respiration in reverse You might have noticed that photosynthesis is the reverse of respiration. Both plants and animals require oxygen and glucose, or another carbon source, for survival. As animals metabolize, they produce carbon dioxide and water vapor as waste products. Plants require carbon dioxide and water and release oxygen and glucose during photosynthesis. This balance between plants and animals is what drives energy flow through ecosystems, as seen in Figure 21.11.

Food Chains Can Form Food Webs

Plants secure usable energy, and animals take advantage of that energy. The simplest depiction of this relationship is to isolate a simple **food chain**, as seen in Figure 21.12. A food chain begins when the producer obtains energy from the sun. The producer—for example, a corn plant—is eaten by a primary consumer. In this case, the herbivore might be a grasshopper. The primary consumer then becomes food for a secondary consumer. Toads, song-

Food chains, trophic levels, and energy consumption • Figure 21.12

A food chain is a sequence of energy consumption and energy transfer by various organisms. A trophic level is an organism's position in the food chain. Energy can't be created or destroyed, but it can change forms. Each change or transformation results in some energy being converted to heat energy, which is usually lost to the environment.

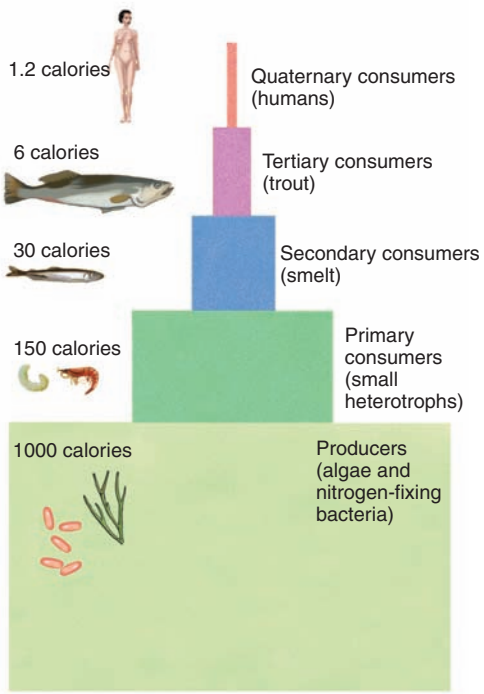


birds, and feral cats all eat grasshoppers. The secondary consumer is in turn captured and eaten by a tertiary consumer, such as a snake or red-tailed hawk.

At each level of the food chain, energy is transferred, but a great deal of energy is lost. In fact, only about 10% of the energy at one level of the food chain is transferred into the tissues of consumers in the level above it. Therefore, only 10% of the energy stored in a plant becomes stored in the herbivore that eats that plant. The carnivore that eats the herbivore gets 10% of the herbivore's energy, and winds up with only 1% of the energy that was stored in the plants that the herbivores ate.

Ecological pyramid: trophic levels and energy loss • Figure 21.13

Each level in the food chain includes less available energy. The width of the bars at each level indicates the energy available from consuming that level. By the fifth trophic level, so little energy is available that a sixth level is not practical.



Trophic levels comprise the ecological pyramid.

Due to the major loss of energy at each level, food chains ideally have no more than five **trophic levels** including the producer. These are usually portrayed in an **ecological pyramid**, as seen in Figure 21.13. The size of each level indicates either assumed energy, measured biomass, or the number of individuals living at each level.

Ecological pyramids give a strong indication of ecosystem stability. The open ocean sometimes has an inverted ecological pyramid, with producers comprising a smaller biomass than primary consumers at a given time. This situation happens in areas where the primary productivity is reduced, perhaps due to extreme wind or temperature changes in the ocean's surface waters. The **phytoplankton** count drops, but the **zooplankton** count remains high. Either the phytoplankton will recover in numbers sufficient to sustain the zooplankton, or the zooplankton will soon thin out due to the food shortage.

trophic level All the organisms that occupy the same energy tier in a community, such as primary producers, primary consumers, or secondary consumers.

phytoplankton Microscopic and macroscopic plants that float in the upper, lighted reaches of the water column.

zooplankton Microscopic and macroscopic animals that float in the water column and move at the mercy of the currents.

Food webs show real-life interactions. To complicate matters, energy does not travel only in a straight line through an ecosystem. For example, many different herbivores consume the same primary producers. In the above example, the corn plants may be eaten by corn borer worms, feral goats, and cattle as well as the grasshoppers. The herbivores could, in turn, become prey to any number of carnivores, or they could die of old age. When many interacting food chains are depicted together, we see a **food web**, as seen in Figure 21.14. The food web more accurately shows the movement of energy through an ecosystem than does a single food chain.

The Hydrologic Cycle Recycles Water Through the Ecosystem

The **hydrologic cycle,** or water cycle, involves the oceans and freshwater. Almost 98% of all the Earth's water is found in the oceans, and glaciers and ice caps contain most of the world's freshwater. Surface water, such as rivers and lakes, only holds 0.04% of the world's water!

Water **evaporates** from the oceans and from freshwater and land. As temperatures increase, evaporation takes place more

evaporates
Changes from a liquid to a vapor through the addition of energy.

Food web • Figure 21.14

The food web of a salt marsh includes an interwoven community of algae, mollusks, fishes, arthropods, birds, and humans. There are many routes to each organism, indicating the many pathways energy can take through the salt marsh.

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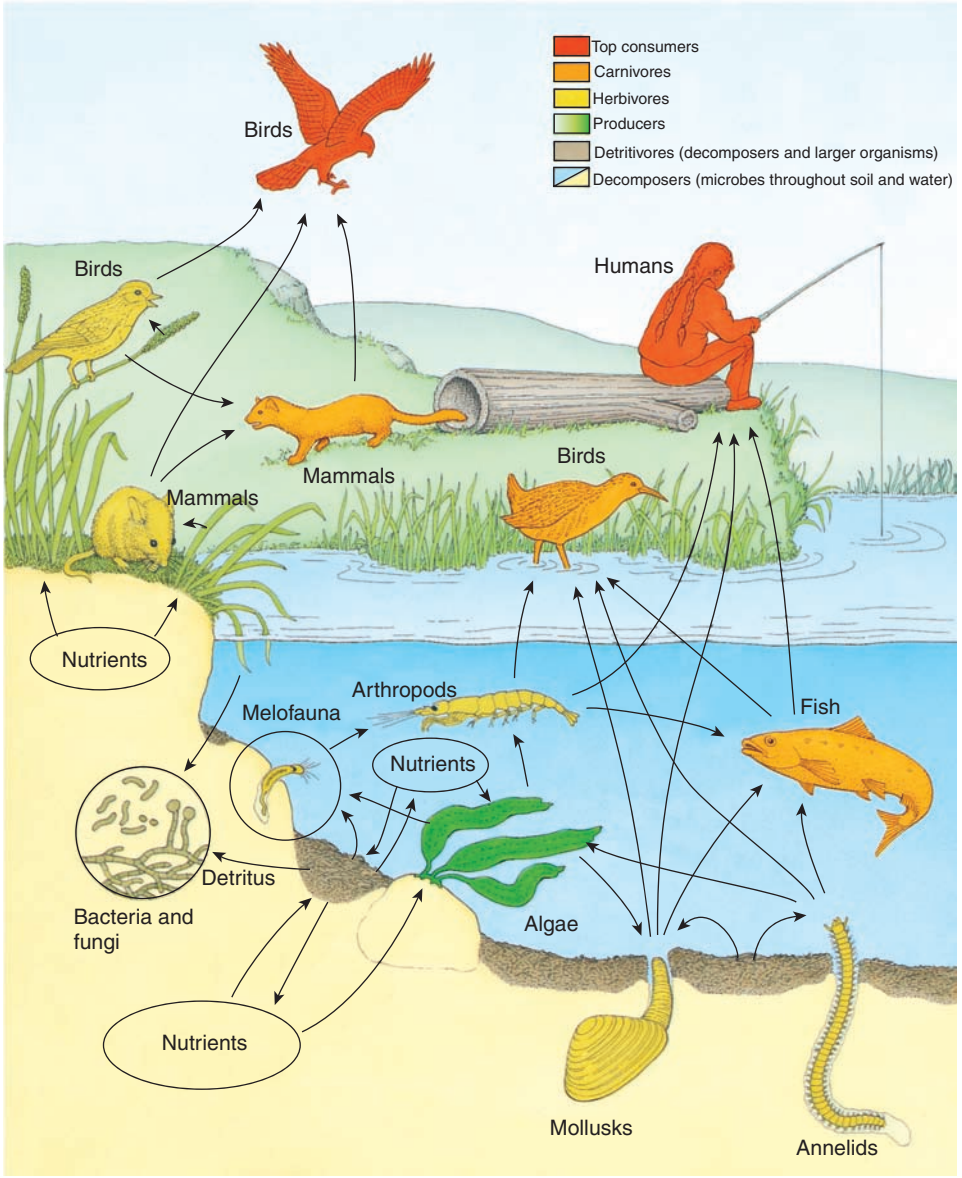
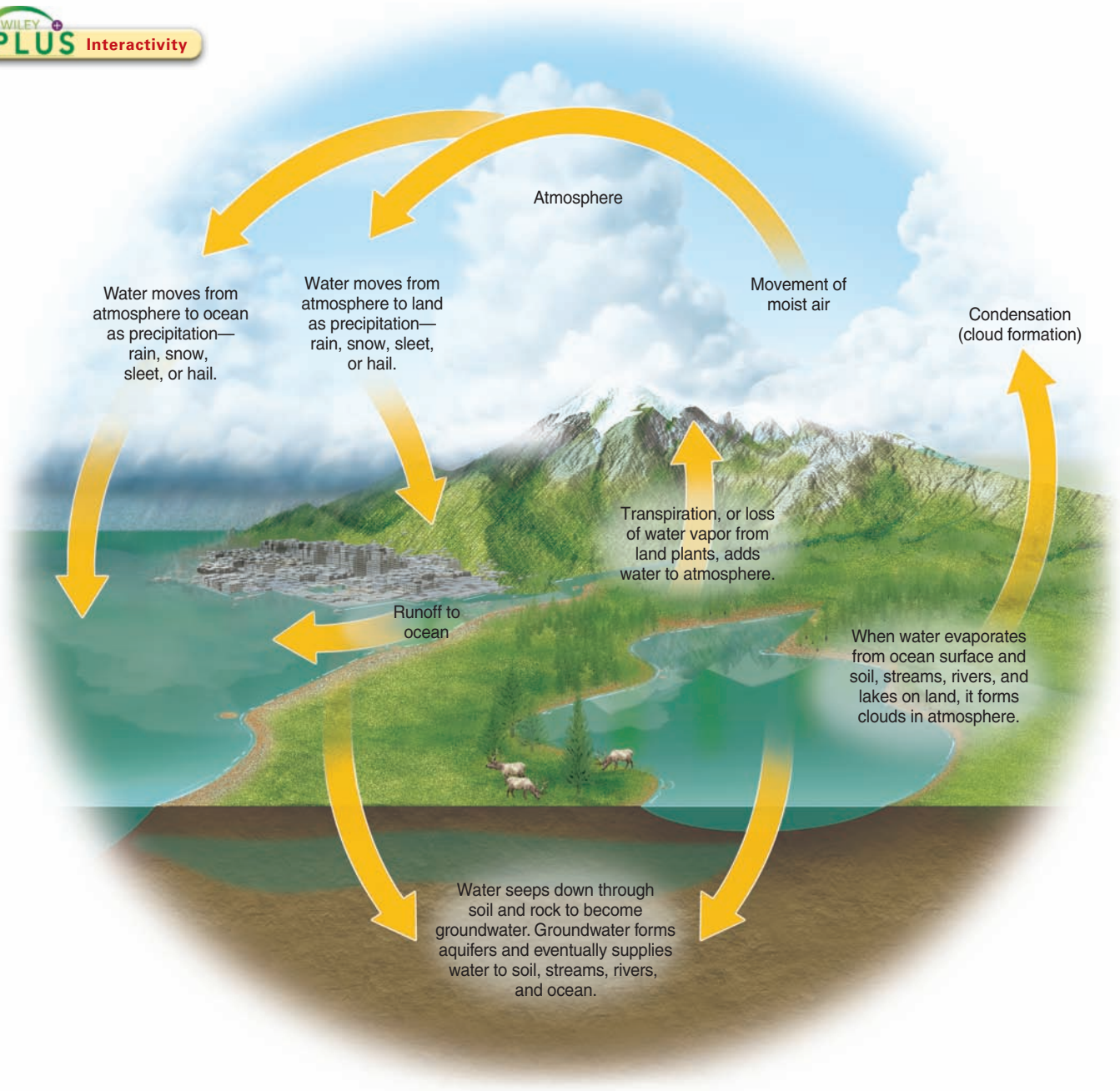


THE PLANNER

Water cycle • Figure 21.15

WILEY PLUS Interactivity



quickly. The water rises into the atmosphere as water vapor and condenses into clouds as the air and water vapor cool. The vapor continues to condense, eventually coalescing into drops that fall back to the land or ocean as **precipitation**.

Because land is above sea level and water naturally seeks the lowest level, surface water eventually returns to the sea. Precipitation over land can either run off into a river or percolate into **groundwater**, which flows underground at various depths. Groundwater saturates the sediment to a constant level called the **water table**, which is where our water wells must reach. A large body of groundwater is called an **aquifer**. Rainfall or snowmelt can recharge an aquifer, as seen in Figure 21.15.

Populated areas often get their drinking water from aquifers. As the human population increases, many aquifers are being drained faster than their recharge rate. This process, called **groundwater mining**, is lowering the water table and will eventually result in a loss of water to these areas.

The Phosphorus Cycle Is a Sedimentary Cycle

Whereas the water cycle includes a large atmospheric portion, the phosphorus cycle is mainly a sedimentary cycle. The phosphorus cycle is shown in Figure 21.16. When some rocks weather, they release phosphate ions into the soil. Plants take up these phosphates through their roots and use them to create phospholipid bilayers, ATP, and DNA or RNA nucleotides. As the plants are eaten, the phosphates move into higher trophic levels. In animal tissue, phosphorus is incorporated into teeth, shell, and bones as well as into ATP, cell membranes, and nucleotides. When organisms decay, the phosphorus returns to the soil. Phosphate may run off the land in rivers and be either absorbed by phytoplankton and seaweeds or lost into sediment. Only when there is an upwelling of bottom sediment will this sedimentary phosphorus return to the biosphere.

The availability of phosphorus is often the limiting factor in the growth of algae, which can have profound effects on the health of the entire community. In 1998, thirteen Florida residents suddenly became ill with skin lesions, nausea, diarrhea, and neurological problems. Their symptoms resembled those in a nearby fishing community and among scientists and tourists in Maryland and North Carolina, which were all blamed on the sudden rapid growth of a toxic single-celled alga. How could people in both Florida and Maryland become ill from a microscopic alga normally found in the water? In the waters off Florida, phosphates and nitrates are exceptionally high. In Florida, 400 million gallons of treated sewage is injected underground daily through 120 wells. The effluent from these wells seeps into the nearby ocean, carrying a high concentration of phosphorus, nitrogen, and other nutrients. Because these nutrients are usually found in such low levels in the oceanic environment, they serve as an external check (in ecological terms, an extrinsic control) on population growth. As more nutrients become available, populations expand. One species that quickly takes advantage of this increased resource is *Pfiesteria piscicida*, an alga that produces the toxin responsible for the symptoms listed above.

The hazards of nutrient dumping have been recognized since the mid-1970s. Laundry detergents used to include phosphates as a cleaning aid, but the excess phosphates in wastewater were **eutrophying** aquatic environments. Although phosphates are banned from detergents in many places, fertilizers are loaded with phosphates and other nutrients. Of course they are, as the job of a fertilizer is to enhance the nutrient level of the soil with just these nutrients! Runoff from farms, golf courses, and lawns that use fertilizer takes these high levels of nutrients into the water supply, creating problems for aquatic ecosystems. As with many environmental concerns, greater public awareness will go a long way toward alleviating the problems.

eutrophying
Encouraging blooms of plants and algae that eventually deplete the resources of a body of water, leading to the destruction of that ecosystem.

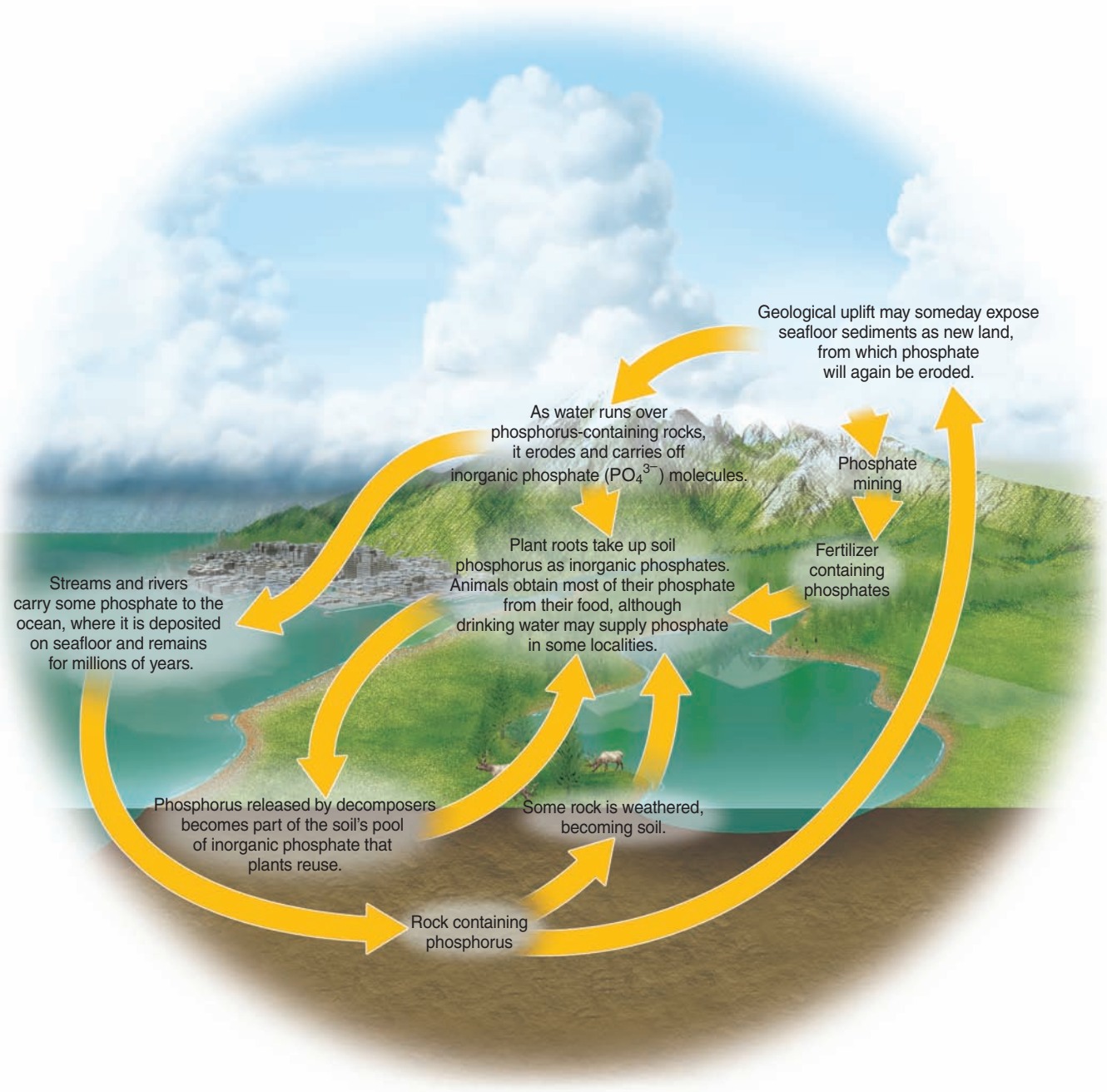
Nitrogen Cycles Between the Soil and the Atmosphere

The majority of the world's nitrogen is in the atmosphere, where it comprises 78% of air's volume. Despite this large reservoir, plants are often starved for nitrogen because they cannot use the molecular nitrogen in the atmosphere. Plants can only use nitrogen that has been "fixed," or converted to organic compounds, in the soil. Fixing reduces nitrogen molecules to **ammonia** (NH_3) or **nitrates** (NO_3^-). Nitrogen fixing is a three-step process. First, one set of bacteria converts atmospheric nitrogen to ammonia; then a second set converts that ammonia in the soil to **nitrites** (NO_2^-). Nitrate-producing bacteria in the soil and plant **root nodules** then convert nitrite to **nitrate**. Once in plant tissues, nitrates are converted to ammonium ions

root nodules
Swellings on the root hairs of legumes and other plants containing nitrogen-fixing bacteria.

THE PLANNER

Phosphorus cycle • Figure 21.16



(NH_4^+), which are found in amino acids and nucleic acids. The cycle is shown in **Figure 21.17** on the following page.

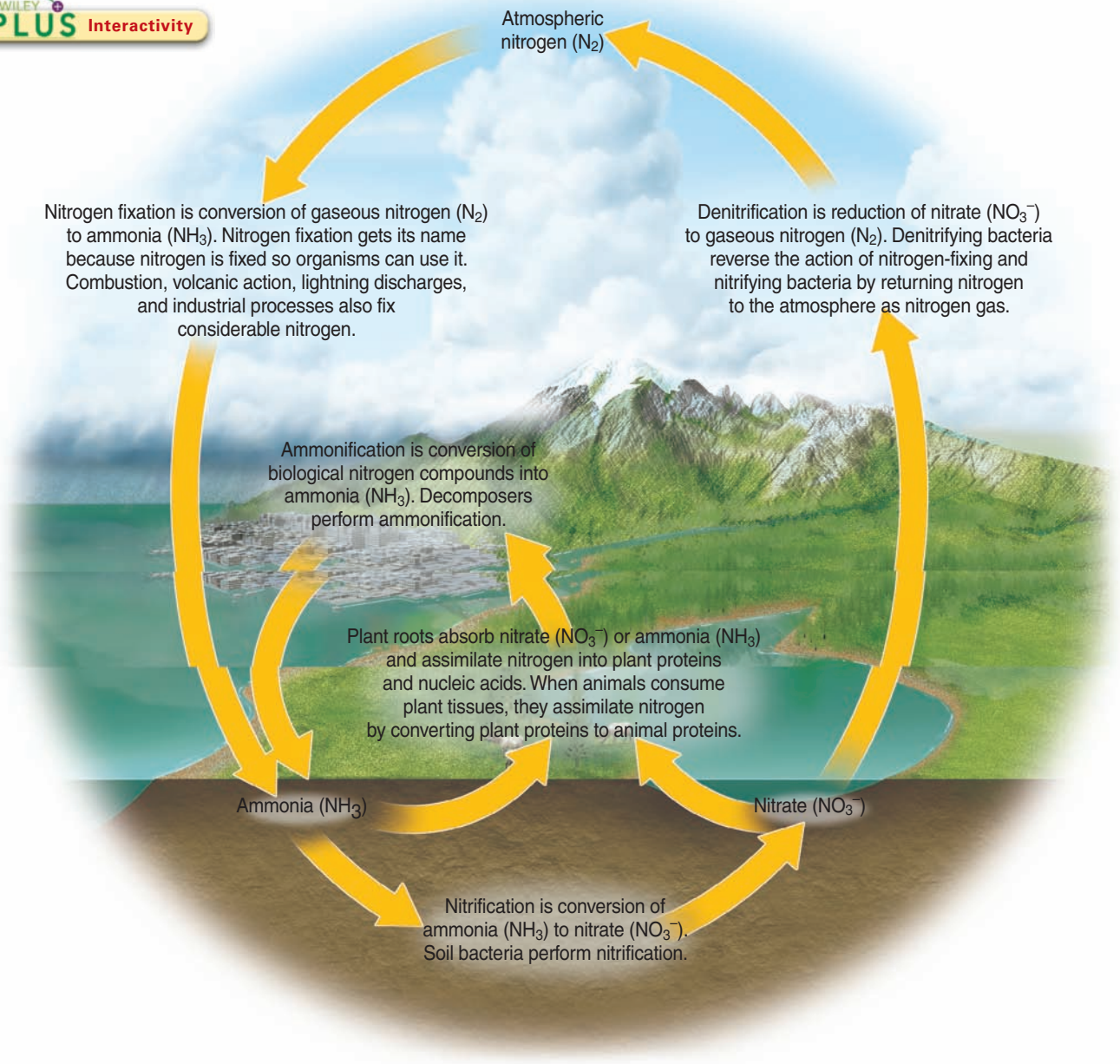
Nitrification occurs when soil bacteria convert ammonia to nitrite and then nitrate in the soil. **Denitrification** is the reverse process, whereby nitrates are converted to nitrous oxide and nitrogen gas, which reenter the atmosphere. Before humans started manufacturing fertilizer, denitrification and nitrogen fixation were balanced at the ecosystem level. Now, excess nitrates are being introduced via fertilizer runoff, adding to our water pollution troubles.

PROCESS DIAGRAM

THE PLANNER

Nitrogen cycle • Figure 21.17

WILEY PLUS Interactivity



Carbon Is Found Almost Everywhere

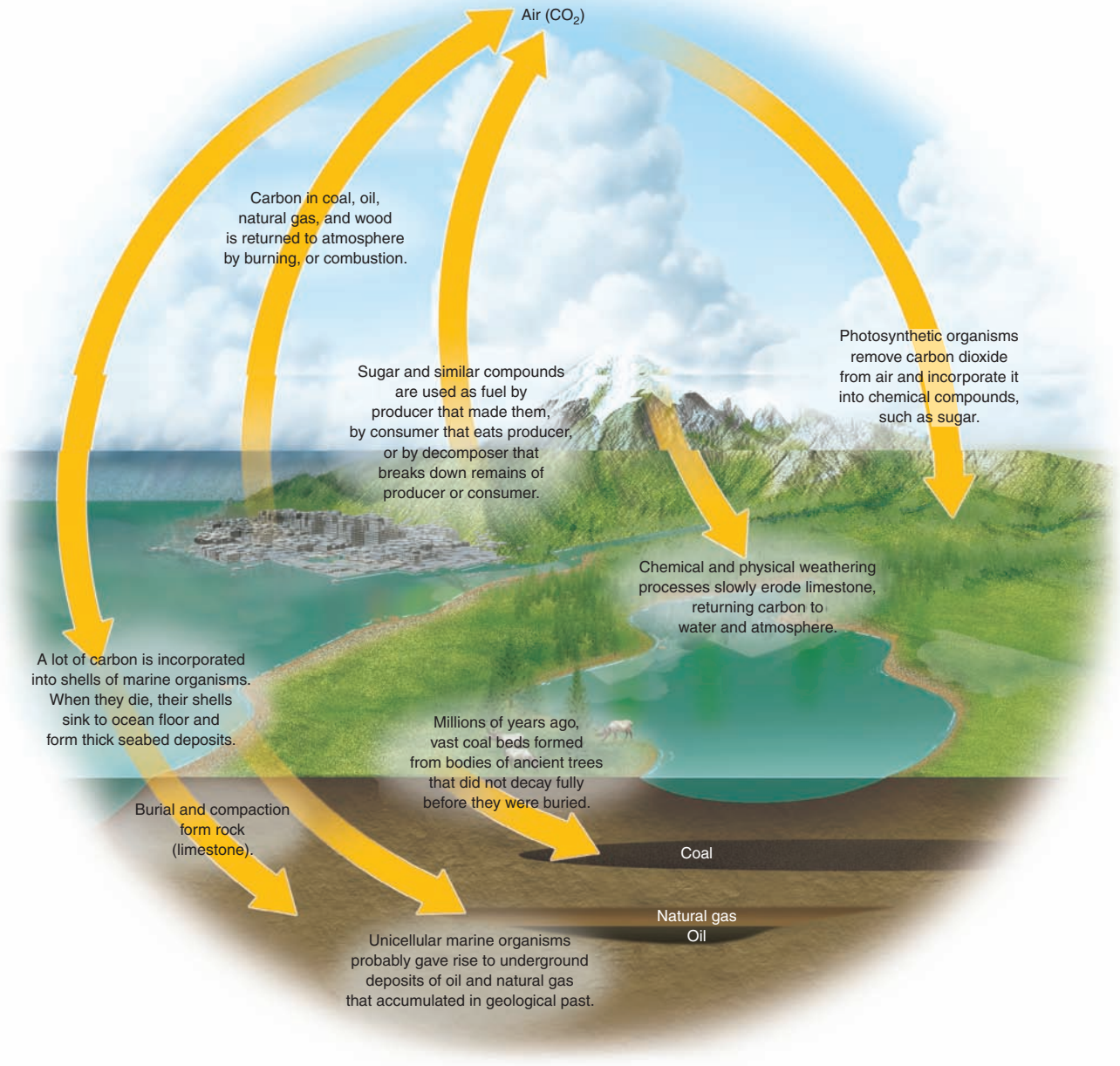
Carbon also cycles through the biosphere. Large carbon reserves are found in many places: oceans, plants, animals, soil, and geologic formations. Moving through these reservoirs, carbon follows either a **short-term** or a **long-term** cycle, as shown in Figure 21.18.

The short-term cycle involves the interactions between the oceans and the biosphere and between the land plants and animals and the atmosphere. This carbon is tied directly to the activities of living organisms. As you know, carbon is taken up during photosynthesis and released during cellular respiration. The rate of removal from the atmosphere by terrestrial plants is about equal to the rate of return through cellular respiration.

The same opposing processes of photosynthesis and cellular respiration also work in the ocean. However, the carbon in the ocean must first diffuse from the atmosphere into the water. Once it enters the water column, carbon is removed via photosynthesis by primary producers, and it is released again by cellular respiration

THE PLANNER

Carbon cycle • Figure 21.18



in the bodies of producers and consumers. A small amount of carbon is lost to ocean-floor sediments, returning to the water column only during upwelling. The amount of carbon in the water column is relatively constant, maintained by constant diffusion with the atmosphere. If aquatic carbon levels increase, more is released into the air.

Carbon also cycles through the sediment, entering the soil community as dead organisms and animal waste.

fossil fuels Energy source derived from organic matter stored in hydrocarbon deposits.

The living biota contains a staggering 800 billion tons of organic carbon, with an additional 1,000 to 3,000 billion tons held in dead or decaying matter in the soil. These either undergo immediate decay, releasing carbon into the atmosphere, or become **fossil fuels**.

Fossil fuels are part of the carbon cycle. Fossil fuels are the basis of the long-term organic carbon cycle. Under the proper geochemical conditions, decaying organic

matter is converted to coal, oil, or natural gas. These fossil fuels are collected and burned for transportation and heat. As humans continually remove and oxidize carbon from the fossil fuel reservoir, the amount of carbon in each pool is shifting. In the last 20 years, there has been a substantial increase in the level of carbon dioxide in the atmosphere, equivalent to approximately 42 billion metric tons of carbon. Not only are we adding carbon to the atmosphere, but we are also reducing the carbon store in plants as we burn rain forests. This reduction in plant material in turn reduces the amount of photosynthesis, exacerbating the shifting carbon levels. With fewer photosynthetic organisms, less carbon is being removed from the atmosphere.

Follow the bouncing carbon atom. If we were to follow a single carbon atom through its cycle, we might see something like the following: You eat a hamburger, taking in the carbon atom as part of a protein molecule. The atom then travels through your small intestine to one of your cells. After that it either stays in your body for the rest of your life as an integral protein or heads to the mitochondrion, where it is oxidized during cellular respiration to become part of a carbon dioxide molecule as an end product of glycolysis. This CO_2 molecule then diffuses into your bloodstream and heads for your lungs. Once there, it is exhaled from your alveoli, at which point it reenters the atmosphere. It is now part of the atmosphere's greenhouse gases, joining the carbon molecules released from the burning of fossil fuels and the use of industrial engines.

In time, your exhaled carbon dioxide molecule may be taken up by a blade of grass or another plant during photosynthesis and converted to glucose, which is stored in the plant. The blade of grass carrying your carbon molecule may be eaten by an herbivore, thus reentering the food chain. Alternatively, it may diffuse from the air to the waters of the ocean and become part of the shell of a microorganism that eventually dies and sends the atom to the bottom of the sea to become part of the ocean floor. There it may remain buried for millions of years or even longer! If the sediment of the ocean floor is lifted and exposed to the atmosphere, it will weather, and your carbon atom may be "freed" to reenter the atmosphere. Regardless of which path the carbon molecule takes, it is unlikely ever to leave the Earth for the next few billion years—until our expanding sun destroys the Earth and the atom enters a new carbon cycle, one best handled by astronomers.

Accumulating carbon in the atmosphere leads to the greenhouse effect. The problem with accumulating carbon in the atmosphere centers on the **greenhouse effect**. Carbon dioxide, methane, and other gases in the atmosphere capture heat radiating from the Earth's surface. Normally, a great deal of this heat escapes into space. However, since greenhouse gases in the atmosphere trap outgoing heat, more of them in the atmosphere means that more heat remains near the Earth, raising the average temperature. In the past century, near-Earth temperatures have risen 0.6°C. This may not sound like much, but most scientists agree: the dangers of global warming are real. Sea levels are rising as glaciers melt. The ice caps on the Antarctic and Greenland are showing signs of instability, further raising the sea level. As recently as July 2008, alarming satellite images showed that a large ice shelf over Greenland had nearly melted away.

Scientists who study ancient climates have seen rapid changes just over a decade or two, proving that climate is not a steady-state affair but a dynamic phenomenon that can change quickly. After many years of discussion and research, scientists are almost unanimous in their assessment. The climate is warming, and almost certainly the increase in human activity has hastened that warming, if not caused it outright. Global warming is likely to cause more intense hurricanes and droughts. We may see more wildfires, tornados, and torrential rainfall, and humans may suffer more deaths due to heat waves. Diseases are moving into new areas. Malaria, for example, is moving into the highlands, which are now warm enough for malarial mosquitoes. Changes in temperature and rainfall could devastate farmlands but perhaps open other areas to the plow.

CONCEPT CHECK 

1. **What** is a habitat? A niche? An ecosystem? A population? A community?
2. **What** are the major biomes and **what** are the characteristics of each?
3. **What** are primary and secondary succession?
4. **What** is a food web, and **what's** an example of a food web?
5. **How** is the water cycle different from the nitrogen and phosphorus cycles?
6. **Why** is the carbon cycle important to life?

21.4 Population Growth Is Regulated by the Environment

LEARNING OBJECTIVES

1. **Relate** carrying capacity to biotic potential.
2. **Discuss** different population growth patterns.

The sizes of populations continually change as they exploit available habitats. The **carrying capacity** of the ecosystem is the number of individuals in each population the area can support indefinitely without permanently reducing the productivity of the area. Carrying capacity represents a balance between resources and competition on one hand and population growth on the other.

Carrying capacity varies with species, with ecological conditions, and with time. Your vegetable garden may be able to sustain only two rabbits, while at the same time supporting thousands of aphids. The carrying capacity for each population is different in that same small plot of land. In each case, the populations in the habitat will grow to the maximum number of individuals the resources can support without intrinsic damage. In natural ecosystems, populations often stabilize near their carrying capacity, but they do not remain static. Instead, they tend to bounce up and down around limits determined by the physical environment. One theory is that under steady environmental conditions, carrying capacity is determined by the limiting resource, often food.

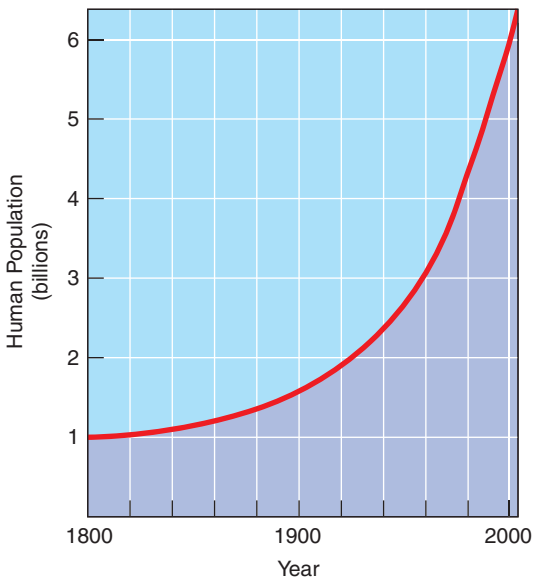
Population Growth Reflects Multiple Factors

The **biotic potential** of a population is its maximum growth rate under ideal conditions. Biotic potential in sexually reproducing populations depends on (1) the number of offspring produced per female, (2) the time to reproductive maturity, (3) the ratio of males to females, and (4) the number of reproductively active individuals. If the population is below the carrying capacity of the environment, most populations grow exponentially, creating a J-shaped curve. Such a curve is seen in **Figure 21.19**.

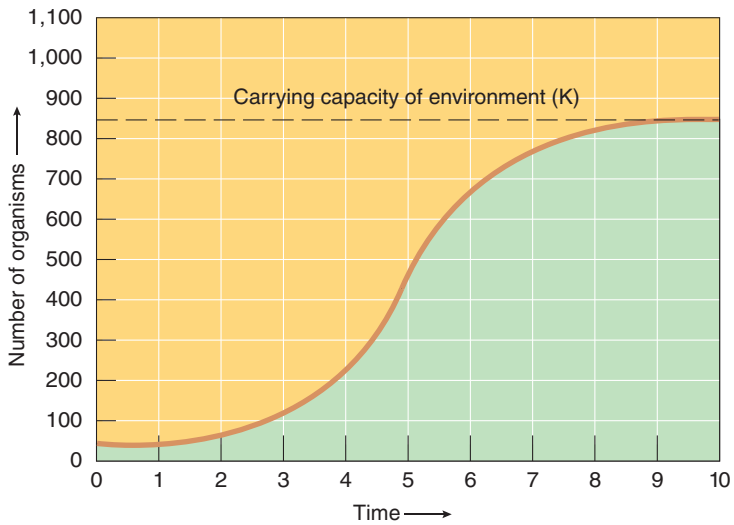
If the population is nearing the carrying capacity of the environment, it expands more slowly and even can begin to oscillate (vary up and down). Its growth tends to form an S-shaped growth curve, as seen in **Figure 21.20**.

Human population growth • Figure 21.19

Human population reached 1 billion after several thousand years, but has been growing exponentially since.

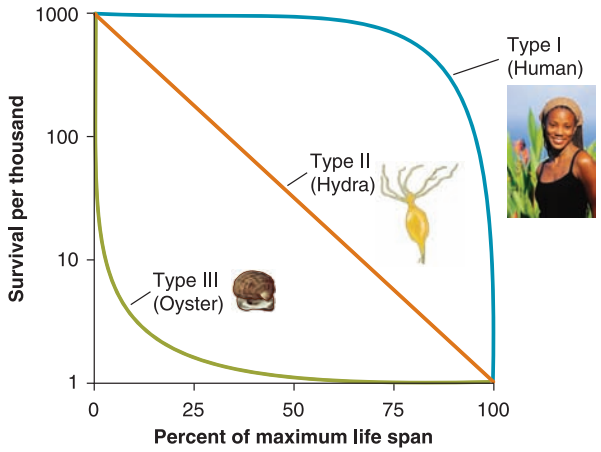


Slowed population growth • Figure 21.20



Survivorship curves • Figure 21.21

A survivorship curve depicts the expected decrease in a population over time. There are three types of survivorship curve:
Type I: These populations produce few young and invest a lot of energy in keeping them alive. Most die-off occurs in old age, resulting in a steep drop in numbers only after many years of life.
Type II: These populations suffer a uniform death rate throughout life, regardless of age of the individual.
Type III: These populations of organisms tend to produce many young, most of which do not survive beyond the first few days or weeks, resulting in an early and steep drop in numbers.



The steeper the growth curve, the faster that population doubles. Under ideal conditions, bacterial population growth curves are quite steep, whereas human population growth curves are much flatter. The average generation time for *E. coli* bacteria is a mere 20 minutes. Humans take a minimum of 12 to 14 years to reach sexual maturity, and many people do not reproduce for some years after that.

The two basic control patterns of population growth are extrinsic and intrinsic control. If the population is extrinsically controlled, organisms colonize new habitat, produce many offspring, invest little energy in each one, and usually widely overshoot the carrying capacity. Because economist Thomas Malthus first described this type of population regulation in his analysis of the human condition, these organisms are called Malthusian strategists.

In contrast, intrinsic control appears among organisms that follow another strategy. These organisms grow and mature more slowly, live longer, produce fewer offspring, and invest more energy per offspring. This slower growth pattern is called logistic strategy. Logistic strategists are usually large animals that prey on smaller ones, while Malthusian strategists tend to be primary producers or animals that eat plants.

A Population Has Three Patterns of Mortality

Extrinsic and intrinsic growth patterns are related to a population's **survivorship curve**, as seen in Figure 21.21. Three basic age distributions show patterns of mortality in a population. Type I survivorship curves describe organisms that provide considerable parental care. Individuals tend to survive through young adulthood and die out at advanced ages. Type II populations have a constant death rate regardless of age. Type III populations produce many young but provide no more than a bit of parental care. Those few individuals that survive infancy are likely to live a long time. The green sea turtle falls into this category. Many eggs hatch, and most of the young return to the sea, but only a handful of the hatchlings survive to reproduce. Once a turtle reaches age 5, however, predation risks drop, and the turtle will probably survive into old age.

Populations rarely reach their biotic potential because competition among individuals for finite resources impedes population growth. Environmental limits on growth include diseases, predation, environmental toxins, and both interpopulation (between two unrelated populations) and intrapopulation (within one population) competition for food, shelter, and water. When environmental conditions deteriorate, the carrying capacity of the ecosystem is reduced, and populations decline. See *I Wonder… How Many People Can the Earth Support?*

Extinction occurs when a population no longer reproduces. Because many herbivores and carnivores can eat multiple food sources, **extinction** is usually rare in ecosystems where humans play no role. When one population in the food web declines, organisms often have other populations they can prey upon to obtain energy, and although populations fluctuate in response to changes in the food web, the animals survive. Extinction occurs when a population is reduced below its ability to reproduce, often by some combination of predation, habitat destruction, and disease.

CONCEPT CHECK STOP

1. **What** is carrying capacity, and **why** is it crucial to understanding population growth? **What** is biotic potential?
2. **How** do survivorship curves relate to population growth patterns?

NATIONAL GEOGRAPHIC

I WONDER...

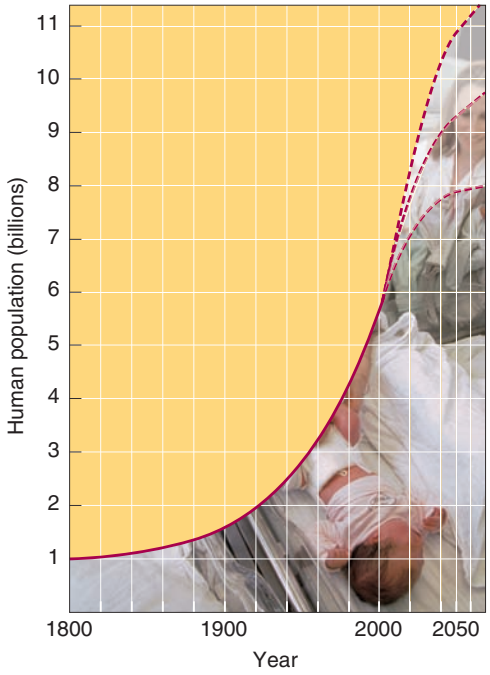
THE PLANNER

How Many People Can the Earth Support?

How many people can the Earth support? Perhaps no question is more important, and yet this question is devilishly difficult to answer. What do we mean by support? Do we mean support as a sprawl of dense cities surrounded by factory farms, with every hectare put "to use"? Is it support as a planet where some nature survives to provide spiritual comfort to its people, where the plants and animals that evolved along with us still live alongside us?

These questions are pressing. Even as the populations of Japan and Western Europe have stabilized, the U.S. population continues to grow about 1% per year. The current population of the Earth, 6.5 billion, could grow past 9 billion by 2050, as shown in the figure. Because Americans have such a high standard of living, our impact exceeds our numbers. As an example of this, the United States uses more than 25% of the world's oil production, even though our population is less than 5% of the total human population.

This impact, however, is not caused by people alone. The best way to view the human impact is with this simple equation: population × affluence per person × technology = impact. Hopefully, the advancing science of environmental economics will provide a better idea of how we can live on the Earth without destroying it. Our decisions should be based on how our actions will affect the seventh generation after us. The long-term goal is to practice sustainable development: in other words, producing the goods we need, while making sure that our grandchildren can do the same.



The United Nations has made three different human population projections, depending on three changing pregnancy rate forecasts.

21.5 Humans Have a Tremendous Impact on the Environment

LEARNING OBJECTIVES

1. **Summarize** the effects of humans on the biosphere.
2. **Define** the origins of smog and acid rain.
3. **Relate** eutrophication to water pollution.
4. **List** three human activities that decrease biodiversity.

Although it seems harsh to view human beings as a plague or a weed on the Earth, there is an element of truth to that description. Humans do not interact with the environment like other animals. When a large number of humans populate an area, they alter the landscape to suit their needs. Rather than die out due to lack of resources, the population continues to increase, and cities spring up where plants and animals once lived. Humans use up local resources and then take from surrounding areas.

Carrying capacity seems to have no meaning to humans. Even in less-industrialized countries, humans are altering the environment to suit their own needs. As the human population grows and industrialization increases, many observers of the global environment are pessimistic that we will be able to solve our problems before they overwhelm us.

Agricultural Practices Are a "Civilized" Use of Our Resources

Humans living in one place tend to drastically alter the vegetation, often planting only one or two species of food crops. A drive through the Midwestern Corn Belt will demonstrate this. **Monoculture** agriculture abounds—there is literally nothing but corn for miles and miles!

monoculture The practice of planting a single species over large tracts of land.

What does this kind of agriculture do to the ecosystem? Originally, the Midwest was short-grass and tall-grass prairie, with hundreds of species of grasses and wildflowers. Insect populations were diverse, occupying myriad niches in the prairie. Larger animals were also represented by a good number of species, including buffalo. When plant diversity is decreased, the ecosystem's ability to support diverse animal life decreases as well. With the same primary producer on acre after acre, ecosystem diversity declines, and so does the resilience of the ecosystem. That one crop year after year pulls a specific set of nutrients from the soil, whereas many different plants remove and replace different nutrients, allowing the soil to maintain its diversity and health. Also, diseases or insects that attack the dominant species could wipe out the entire crop, further reducing the diversity of the area.

Of course, hunger is a basic human drive, one that we must constantly work to satisfy, and monoculture does provide vast quantities of food. Currently, some agricultural research is focusing on the quest to produce quality food with minimal environmental devastation; this is called sustainable agriculture.

NATIONAL GEOGRAPHIC

WHAT A SCIENTIST SEES

Where Does All the Garbage Go?

WILEY PLUS Video

The daily per capita solid waste production of the United States has almost doubled since 1960. The bury-and-forget approach to garbage came under fire in the 1970s, when plumes of groundwater pollution were detected streaming away from garbage dumps. At the same time, municipalities have had more difficulty finding landfill sites, and the cost of disposal is starting to soar.

These factors have created a fertile ground for recycling, especially as energy prices soared after the two oil crises of the 1970s and again in the late 2000s with the ongoing turmoil in the Middle East. Why throw out an aluminum can when it takes so much electrical energy to refine the aluminum to replace it? In the 1980s, recycling started to play a major role in reducing the amount of garbage. Beyond reducing the need for landfills, recycling can reduce the impact of mining or logging to produce raw material and also cut fuel use and air pollution.

Different countries have different approaches to recycling. In Europe, small-appliance manufacturers are required to take their products back at the end of their lifetime, which creates a strong incentive to manufacture products that are easy to recycle. In Japan, a conservation ethic, combined with much higher population density, has led to extremely high recycling rates.

Here in the United States, there is much more that can be done. We recycle less than a third of the municipal solid waste we create. Both promoting markets for recycled materials and buying recycled material can help raise the incentive to recycle.

Think Critically

1. Why do you think the United States is not more active in recycling?
2. Should we initiate government regulations on recycling and using recycled goods?
3. Are there alternatives to recycling that may help reduce our waste disposal problems? What are these alternatives, and again why do you think the United States has not taken advantage of these technologies?

Water and Air Pollution Are Human Health Issues

Other ecosystem damage comes from widespread pollution of water, soil, and air. Air pollution includes anything suspended in the atmosphere that decreases the quality of life for those organisms breathing it. Polluted air causes problems in the respiratory tracts of organisms, either by adding particles that clog or damage respiratory membranes or by creating compounds that otherwise harm the body's tissues.

Water pollution deprives us of water's usual benefits. Adding too many chemicals to water prevents us from using that water for industrial or personal needs. Soil can also be contaminated with persistent toxic compounds. These get into the soil through human activities and include salts, pesticides, radioactive materials, or biological factors, such as pathogenic bacteria or viruses. Finally, ordinary garbage can also pose an environmental problem. See *What a Scientist Sees: Where Does All the Garbage Go?*

Air pollution includes smog and acid rain. **Smog** is a general term for nitrogen oxides and hydrocarbons that, in sunlight, turn a brown or gray and form smog. Smog contains **PAN (peroxyacetyl nitrates)** and ozone, both of which irritate mucous membranes in the eyes and respiratory tract. Ozone is helpful in the upper atmosphere, but closer to the ground it can make serious diseases like asthma and emphysema even worse. Regulations on automotive and industrial emissions have reduced smog in some countries, but the problem is by no means solved.

Acid rain is caused by the release of compounds that can convert to acids in the atmosphere and is shown in Figure 21.22. The largest source of acid rain is **sulfur oxides** (SO_2 and SO_3) released from burning fossil fuels. These oxides combine with water vapor to form sulfuric acid. The acid falls back to the Earth as acid rain, damaging biotic and abiotic structures alike. Regulations in some places require industries to reduce sulfur dioxide emissions. **Scrubbers** reduce sulfur emissions from coal-fired electric generators, for example, and automobile manufacturers must meet minimum standards for tailpipe emissions.

scrubbers
Equipment in a smokestack that removes impurities from the escaping gas.

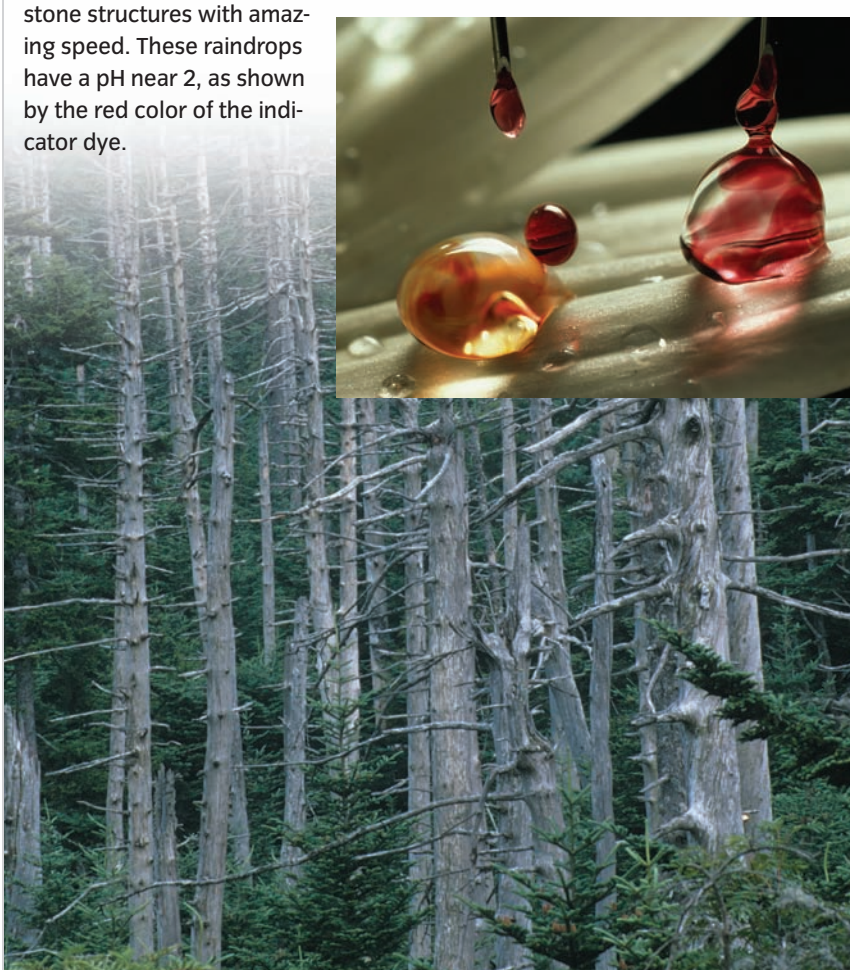
Water pollution is a serious threat. The atmosphere is not the only resource that can be damaged by human activity. Water pollution is a serious threat. As mentioned, there is precious little available freshwater. We water crops, cool factory machinery and electric generators, and flush away feces and urine with freshwater, and all of these actions pollute the water. Organic or inorganic nutrients, as well as toxic chemicals, can pollute water. Organic nutrients include compounds from sewage treatment plants, paper mills, and food-processing factories. Inorganic nutrients usually come from fertilizer runoff.

One consequence of water pollution is **eutrophication**. When nutrient levels skyrocket in a shallow body of freshwater, plant life multiplies rapidly. Eventually, the excess mass of producers will die, and the decomposers will work on the biomass. The death and decomposition of these plants reduces the water's oxygen concentration, killing fishes and invertebrates. Eutrophication is a natural process that converts ponds to wetlands and dry land, but human activity greatly increases its rate.

Groundwater can be polluted as chemicals percolate from the surface into the groundwater. This is doubly troublesome, as groundwater serves as drinking water sources for the majority of humans. The slow **turnover** of groundwater means that those pollutants will remain in the aquifer for many years.

Acid rain • Figure 21.22

Acid rain can cause widespread death of vegetation and can lower the pH of lakes and ponds to the point where nothing can survive. The acidity of the water can also erode both synthetic and natural stone structures with amazing speed. These raindrops have a pH near 2, as shown by the red color of the indicator dye.



Environmental Protection Legislation Works

In many parts of the globe, legislatures have attempted to curb the destruction of the environment by passing laws limiting air and water pollution. For example, a 1987 international forum called the Montreal Protocol began the phaseout of CFCs (**chlorofluorocarbons**). CFCs were used in air conditioners and refrigerators until scientists discovered that they deplete the **ozone layer** after being released into the atmosphere. Ozone (O_3) in the upper atmosphere blocks harmful ultraviolet radiation that can cause cancer and other problems in the biosphere. CFCs released near the Earth's surface rise to the **stratosphere** where the chlorine destroys ozone. In the mid-1980s, scientists discovered a gap in the ozone layer over Antarctica. In subsequent years, this gap became a giant hole and raised the prospect of widespread biological damage through UV radiation. Since the CFC phaseout began, this hole has begun to close. CFCs are stable and will remain in the atmosphere for a long period, but the episode does show that global action can slow or reverse a clear environmental threat.

chlorofluorocarbons Compounds made of hydrogen, carbon, fluorine, and chlorine, once used as refrigerants.

stratosphere The portion of the atmosphere from about 15 to 50 km above the Earth; contains the ozone layer.

Americans Are Not Alone in Their Use and Abuse of Resources

This discussion has centered on activities of the U.S. population because the U.S. economy uses and, some say, abuses so many resources: 22 tons of fuel, metals, minerals, food and forest products per person, per year. All of these materials are used to construct cities, suburbs, and roads, to drive long distances in our 250 million cars and trucks; we also allow soil erosion in our one-crop farming system and divert waterways to suit our needs. Some scientists have estimated that the typical American consumes 88 tons of resources per year.

Americans are not alone in their use of resources. For example, in recent years, Asia consumed 2,370,000 thousand metric tons of fossil fuel. During the same year, the Middle East consumed 560,000 thousand metric tons, Europe consumed 3,038,000 thousand metric tons, and North America consumed 2,157,000 thousand metric tons. Another resource that the world uses at a tremendous rate is paper and paper products. Amazingly, in one year's time, 103,861,000 metric tons of paper were used in Asia; 7,260,000 tons were used in the Middle East and North Africa; 94,191,000 tons in Europe; and 101,058,000 tons by the North American population.

Around the world, people are moving into urban areas that are rapidly expanding to take over the countryside. In the United States, **urban sprawl** is eating up valuable farmland as we turn rural areas into housing divisions and bedroom communities. Eventually, as the population rises, we could regret the day we decided that farmland was ideal for growing subdivisions. See **Figure 21.23** for more on the human impact.

Human Activity Has Been a Factor in Decreasing Biodiversity

Biodiversity is a measure of species richness, measured at any one of three levels. **Genetic diversity** is the variation in individuals in a population. Genetic diversity promotes reproductive success and is the raw material for adaptation. **Species diversity** is the number of species alive today. Taxonomists believe there are at least 30 million species on the Earth, but some estimates run up to 80 million. **Community diversity** measures the diverse forms of life living together in a community.

Human activity tends to decrease biodiversity, as we alter landscapes and force animals and plants to move or die out. Removing habitat through farming, construction, mining, or recreation can cause extinction. When we pollute the environment, overfish, or overhunt animals, we cause extinction. We can even cause extinction by bringing new species to an environment. These organisms may have no natural predators in the new ecosystem and can thus outcompete native organisms. Introduced species often take over large parts of ecosystems, preying on **endemic** and **indigenous** species or otherwise destroying the natural balance of the ecosystem.

endemic Native to a region.

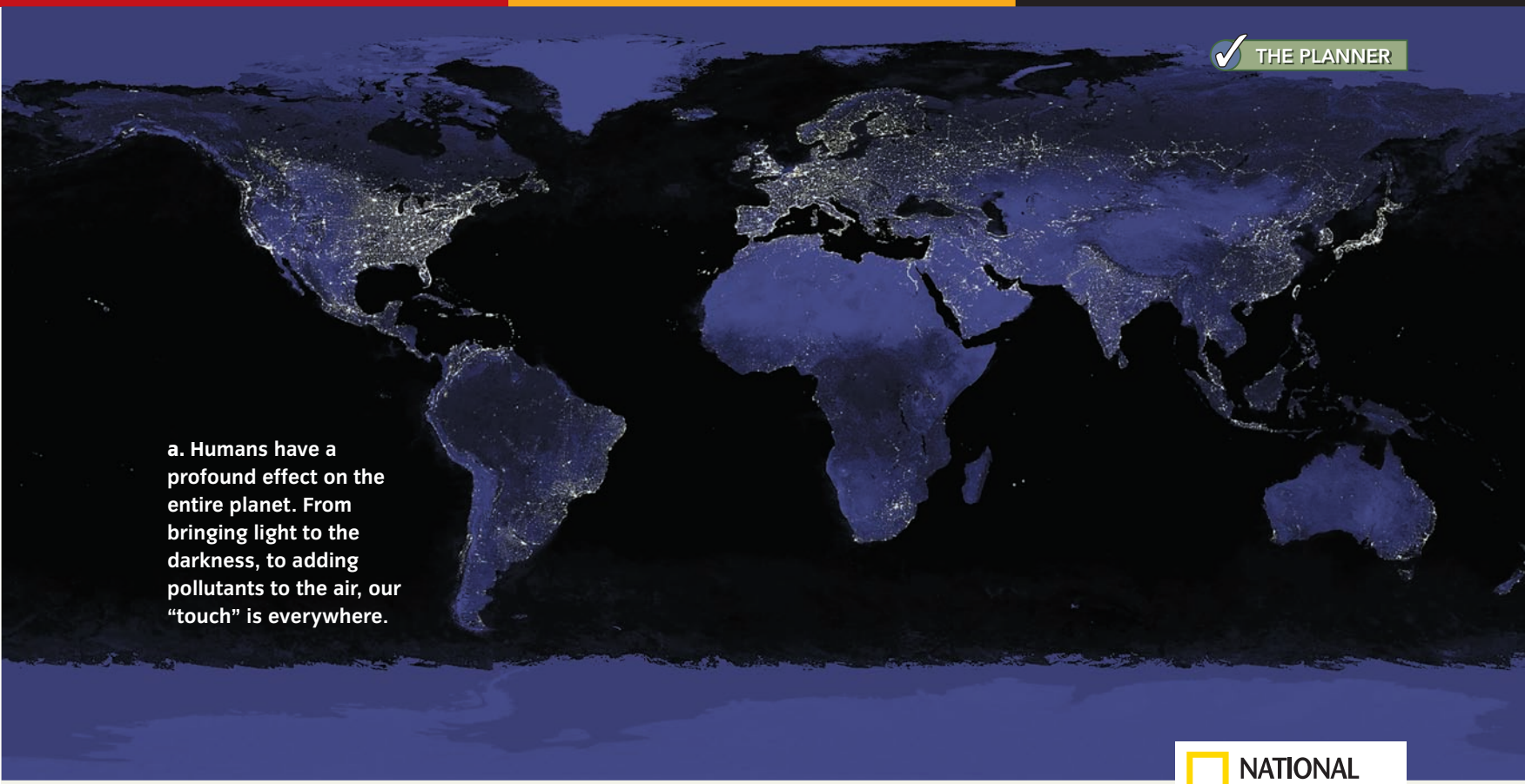
indigenous Found only in a particular region.

Introduced species can destroy ecosystems.

Hawaii and other remote islands are currently fighting the introduction of new species, which have an especially easy time colonizing remote ecosystems. One good example comes from the introduction of the brown tree snake (*Boiga irregularis*) to Guam between 1945 and 1952. The snake probably arrived as a stowaway on a ship. With no natural predators and an abundance of easy prey, the brown tree snake population boomed, eating birds, lizards, bird and reptile eggs, even pets. The brown tree snake populations grew so large that villages would suffer power outages as

Biological InSight

The human impact • **Figure 21.23**



a. Humans have a profound effect on the entire planet. From bringing light to the darkness, to adding pollutants to the air, our "touch" is everywhere.

WILEY PLUS Video

b. The human impact is not limited to light and air pollution. We have polluted water and soil, deforested vast tracts of land, and caused expansion of deserts with our questionable agricultural practices. Additionally, we "spill" oil in our oceans, emit greenhouse gases into our atmosphere, and generally disrupt ecosystems with our "advances."

ETHICS AND ISSUES

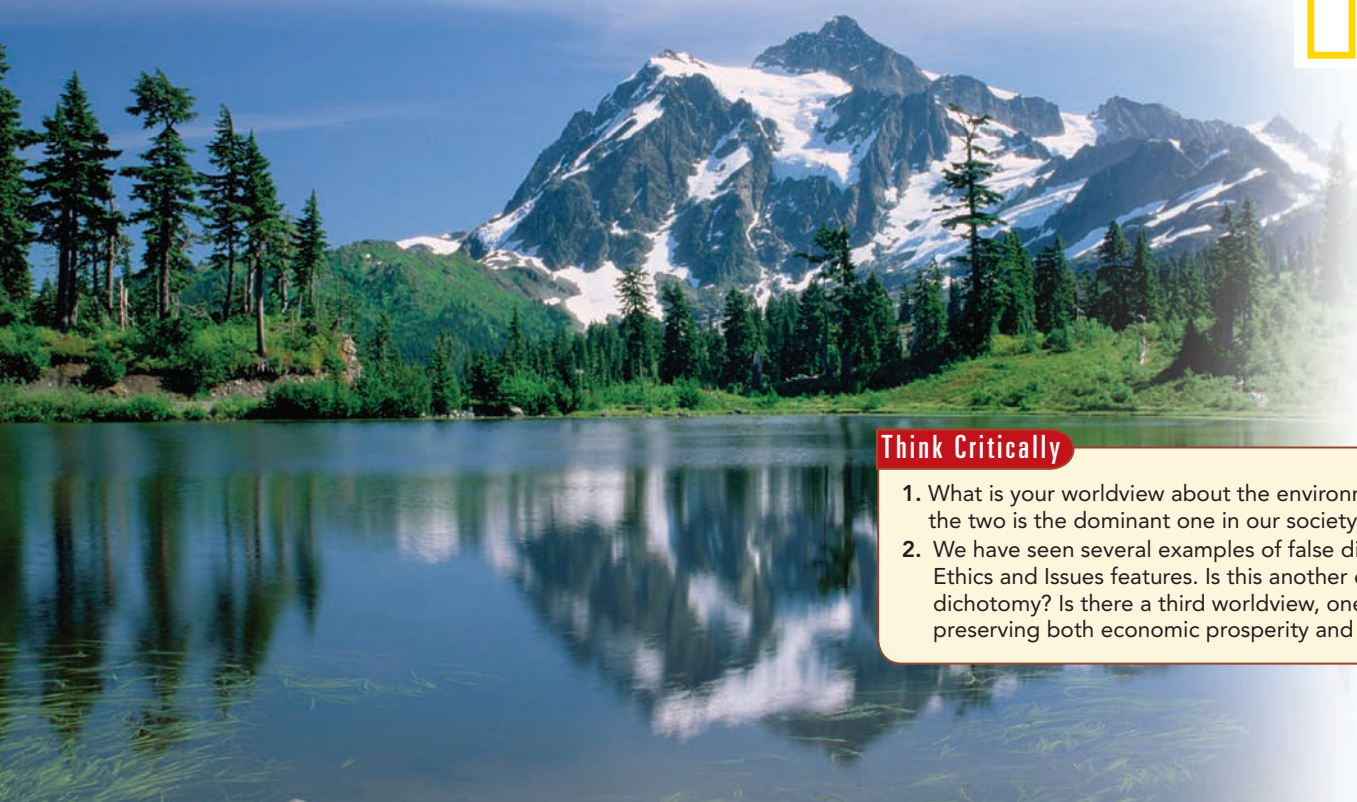
THE PLANNER

Which Worldview Do You Have?

We all have a worldview about our natural environment, a set of assumptions that we carry around with us even if we are unaware of them. Environmentalists long ago identified two very different worldviews, often using different terms but usually with these two themes:

1. *The Expansionist.* Humans dominate the Earth and use its bounty and nearly unlimited resources to benefit humankind. Our ingenuity and technological advances will ensure that we continue to expand the world's ability to support us, as we have in the past. Yes, we must manage these resources, but with the aim of maximizing their yield, often through privatization—because private owners protect their investments, they will protect any resources they own. Progress and growth will continue indefinitely and thus continually expand opportunities for wealth.
2. *The Conservationist*. Humans should not dominate the Earth but instead should protect both resources and all nonhuman life-forms—not just manage them for a profit. We have adapted to a specific set of environmental conditions that can't be changed significantly without threatening our long-term health and even survival. Resources are limited, especially when we think about future generations. Some growth and "progress" harms the environment and needs to be discouraged through taxation or other means. The atmosphere, oceans, and rivers cannot be privatized, and private ownership often leads to short-term exploitation rather than long-term sustainability.

Critical Reasoning Issues People using the same data and critical reasoning skills can come to different conclusions if they start with different assumptions. They have different frames of reference.



Think Critically

1. What is your worldview about the environment? Which of the two is the dominant one in our society today?
2. We have seen several examples of false dichotomy in our Ethics and Issues features. Is this another example of a false dichotomy? Is there a third worldview, one that focuses on preserving both economic prosperity and ecosystems?

the weight of snakes basking on power lines caused them to snap. Eventually, the snake exterminated most of the small vertebrate populations of the forests in Guam, including birds and mammals. To this day the island is eerily quiet due to the lack of birds. Control efforts are underway, as are strict monitoring programs on neighboring islands, where this snake could cause similar havoc. In Hawaii, the brown tree snake would cause an ecological disaster similar to the one it caused in Guam. The Hawaiian Islands are already fighting ecological invaders like the little red fire ants, coqui frogs, and miconia plants. Each of these invaders is capable of harming the Islands' precious biodiversity by outcompeting endemic species and pushing them toward extinction.

Species extinction is a worldwide problem. Although oceanic islands are an extreme example, species extinctions are worldwide problems. In the last century, 10% of the 297 known mussel and clam species and 40 of about 950 freshwater fishes in North America have disappeared. Plants and animals of the rain forests, as well as coral reefs, are also threatened. Although biologists cannot predict exactly how accelerating global warming and global growth will affect extinctions, most expect the problem to intensify.

Due mainly to human activity, the current extinction rate is estimated to be 100 to 1,000 times higher than in recent history. Dr. Donald Levin, a researcher at the University of Texas at Austin, claims that one additional species becomes extinct every 20 minutes. He predicts that within 200 to 300 years the Earth will lose at least half of all animal and plant species. We could be in the early stages of a sixth major extinction, since the current rate is higher than that at any time except during the five mass extinctions in geological history. This is reason for concern.

The ecological future is not pretty. An increasing population needs more food. We abuse our resources and produce more waste. Some steps toward **sustainability** include better waste treatment, land and water conservation, planned community growth, reduced population growth, smarter use of energy, and more recycling. These steps may seem small, but they can move us in the right direction. The primary reason for hope is this: Human beings are phenomenally creative and inventive! See *Ethics and Issues: Which Worldview Do You Have?*

sustainability The wise exploitation of resources and energy, to ensure resources for future generations.

Life on Earth Goes On

Throughout this book, we have studied the processes and concepts of biology through the human organism. We began with what it means to be alive, and we gave a short explanation of the classification of humans and our origins. From there, we progressed through biochemistry, cells, tissues, and organ systems. We discussed the notion of homeostasis and described how major body processes continuously attempt to restore balance. Throughout, we have explored how the human animal fits into the environment, and finally we discussed how humans have affected the whole planet.

As your understanding of life processes increased, we added more ecological and evolutionary ideas. Social consciousness, environmental awareness, and critical reasoning were underlying themes throughout the chapters—ethical dilemmas regarding the effects and consequences of science and technology abound in all cultures. Hopefully, as you complete this book, you are feeling better prepared to make sound political and social decisions based on facts. Your decisions and opinions are firmly grounded in understanding and should not be swayed by partial or misleading arguments, whether they come from friends, family, politicians, or the media.

Be conscious of your own worldview, and work to understand that of others. Life will go on, and if you lend it your expertise, reasoning, and gifts, it will be much sweeter for all.

Anthropologist Margaret Mead once wrote that not only can a small number of informed and dedicated citizens change the world—they are the only people who have ever changed it. Be one of the informed and dedicated citizens who change our world.

CONCEPT CHECK STOP

1. **What** are the environmental effects of our modern agricultural practices?
2. **What** is the primary cause of acid rain? Of smog?
3. **What** is the relationship between water pollution and eutrophication?
4. **What** are three human activities that reduce biodiversity?

Summary

THE PLANNER

1 The Theory of Evolution Is the Foundation of Biology 594

- Charles Darwin proposed the theory of evolution in 1859 to explain the diversity of life on the Earth.
- Evolution is a change in allele frequencies in a population over time. Creationism and intelligent design are nonscientific explanations for life.
- Darwin's theory is based on natural selection and can be quantified with the Hardy–Weinberg equation.

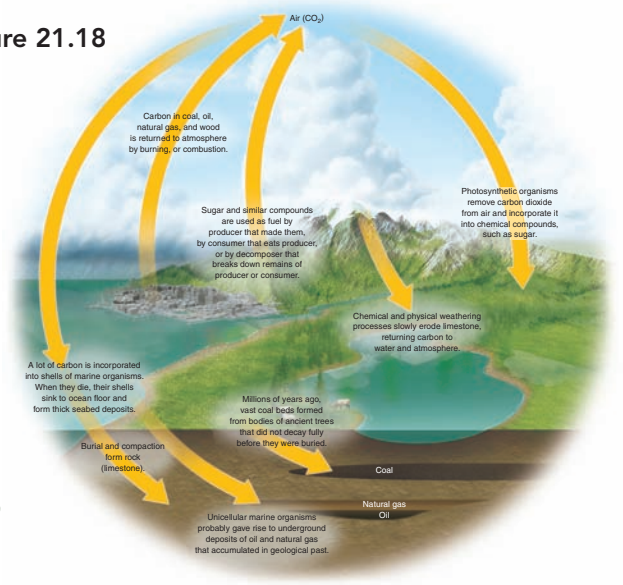
2 Natural Selection Has Far-Reaching Effects on Populations 599

- Natural selection can alter the allele frequency of a population by reducing the number of less-fit or unfit individuals.
- Allele frequencies are also altered via the bottleneck effect, the founder effect, and gene flow.

3 Ecosystems Sustain Life 602

- Ecology is the study of organisms and their interactions with one another and the environment.
- Individuals of the same species make up a population. The many populations in an area define a community. Ecosystems are composed of all the communities in a larger geographical area. The entire Earth is referred to as the biosphere when discussed in ecological terms. Ecosystems can be defined by the dominant organisms and are grouped in nine categories of biomes. When a biome is new, organisms fill the available niches in predictable patterns.
- Primary succession occurs on newly created land, whereas secondary succession takes place after a devastating fire or other disaster.

Figure 21.18

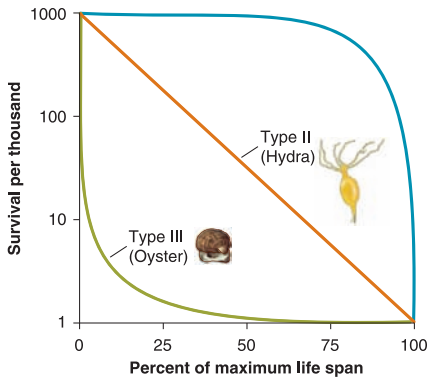


- Energy flows through an ecosystem, whereas nutrients usually cycle within it, as shown here. Energy is constantly lost as heat, and it is gained from sunlight. Nutrients cycle through a gaseous or a sedimentary cycle. Carbon, water, nitrogen, and phosphorus are the main nutrients that ecologists study. Phosphorus is mainly stored in the ground, whereas nitrogen and water have a strong atmospheric component. The reality of global warming, caused largely by carbon dioxide accumulation in the atmosphere, has focused special attention on the carbon cycle.

4 Population Growth Is Regulated by the Environment 617

- Mortality rates indicate the health of a population. When carrying capacity is reached, organisms cannot obtain needed resources and the population declines.
- As the population dips below carrying capacity, organisms find resources more easily, and the population again increases. This oscillation is natural. Growth curves of biotic potential can start steeply and then level off, or they can start out flat and then increase with age. Malthusian strategists have many offspring and tend to overshoot carrying capacity. Mortality curves can show three trends.
- Type I organisms have few offspring but provide extensive care for them. As you can see here, Type II organisms are apt to perish at any point in their life cycle. Type III organisms show a high infant mortality rate, with a subsequent leveling of mortality in adulthood.

Figure 21.21



5 Humans Have a Tremendous Impact on the Environment 619

- Humans upset the natural balance of ecosystems every day. We pollute the waters, add particle pollution to the air, and speed the process of eutrophication in freshwater lakes and ponds.
- We can destroy biodiversity and speed the loss of endemic and indigenous species. These challenges will not go away with wishful thinking alone.

Key Terms

- biome 602
- chlorofluorocarbons 622
- chlorophyll 606
- climax community 605
- consumers 606
- creationism 595
- divergent 598
- dominant population 603
- endemic 622
- energy 606
- eutrophying 612
- evaporates 610
- fitness 598
- fossil fuels 615
- gene flow 596
- genetic drift 596
- hydrolyzed 608
- indigenous 622
- intelligent design 595
- macroevolution 596
- microevolution 596
- monoculture 620
- photopigment 606
- phytoplankton 609
- pioneer species 604
- producers 606
- root nodules 612
- scrubbers 621
- selection pressure 596
- stratosphere 622
- sustainability 625
- trophic level 609
- zooplankton 609

Critical and Creative Thinking Questions

1. Describe your population, your community, and your ecosystem.
2. Relate the survivorship curves to those factors that contribute to the mortality of each type of organism.
3. Diagram the process of photosynthesis. Using the products shown in your diagram, continue the flow to show how respiration is related to photosynthesis.
4. Some people believe that being a vegan is the most responsible way to get nutrients while still maintaining the balance of the ecosystem. Explain this rationale, giving solid information that supports or discredits this claim.
5. **CLINICAL CLICK QUESTION**
   Every year for the past twenty years, Gordon and his friends had gone to the Catskill Mountains in upstate New York for a fishing trip. Over the years, they noticed that good-size fish were harder and harder to find. In 2003, Gordon was unable to make the trip for health reasons. When he was finally able to join his friends again in 2009, he was astonished by the changes he saw. There was a noticeable decrease in fish populations, specifically in trout and bass. When he investigated further he discovered that the invertebrate populations were also affected. Populations of clams, snails, and crayfish that had once been abundant were now very small or gone altogether. A quick scan of the forest surrounding the lake revealed that the tops of the trees were not leafy, and in fact many of the taller trees appeared dead. As a final test, Gordon tasted the water. He found it to be slightly metallic tasting, with a sharp bite that he was not expecting. What might be affecting Gordon's fishing hole? Remember that this is relatively close to New York City. Why does the water have that sharp bite to it? Are the dead trees related to the loss of snail populations? If so, how? For help in diagnosing the damage to this environment, visit http://www.epa.gov/acidrain/effects/surface_water.html.

What is happening in this picture?

In this image, small steps are being taken to alleviate some of the stresses on the environment. Proper disposal of trash prevents that trash from decomposing on the vegetation or in the water. It also prevents animals from ingesting these materials and dying from filling their stomachs with plastics. Individual responses to ecological injustices do make a difference, as do legal requirements to reclaim, recycle, and reuse potentially toxic products.

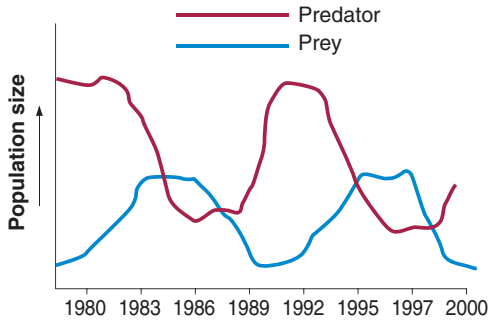
Think Critically

1. What effect might the buildup of trash have on the biota (animals) of this area? How might this affect the evolution of organisms, such as insects, bacteria, or amphibians?
2. How might reclamation efforts be improved in your community?
3. What is the meaning of the following quote by B. Dioum? Explain this in your own words, personalizing your answer with the knowledge you have gained throughout this text.
   "In the end, we will protect only what we love, we will love only what we understand and we will understand only what we are taught...."

Self-Test

1. The proper order of terms, from most inclusive (largest grouping) to least inclusive (smallest grouping) is _____.
   a. biosphere, ecosystem, community, population, individual
   b. ecosystem, population, community, biosphere, individual
   c. population, community, biosphere, ecosystem, individual
   d. community, population, ecosystem, biosphere, individual

2. The graph below shows that _____.
   a. prey populations are uncontrolled and grow exponentially
   b. predator populations are always smaller than prey populations
   c. predator population trends mirror prey population trends, with some delay
   d. there is no relationship between predator and prey population sizes



3. Which of the following would NOT be included in a farm-town community?
   a. people
   b. farm animals
   c. farm crops
   d. soil type

4. The biome pictured here is the _____.
   a. temperate grasslands
   b. tundra
   c. tropical rainforest
   d. chaparral

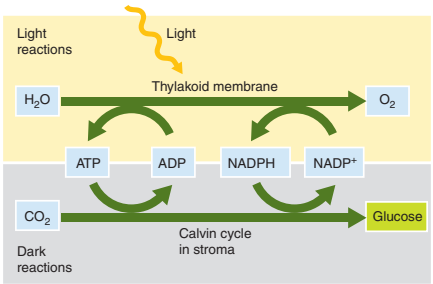
5. The biome with the least amount of yearly rainfall is the _____.
   a. savanna
   b. chaparral
   c. desert
   d. tundra

6. A clear-cut portion of the rain forest that is abandoned and allowed to return to the natural state is an example of _____.
   a. primary succession
   b. climax community
   c. secondary succession
   d. partitioned succession

7. All plants that grow quickly and take over an area are considered pioneer species.
   a. True
   b. False

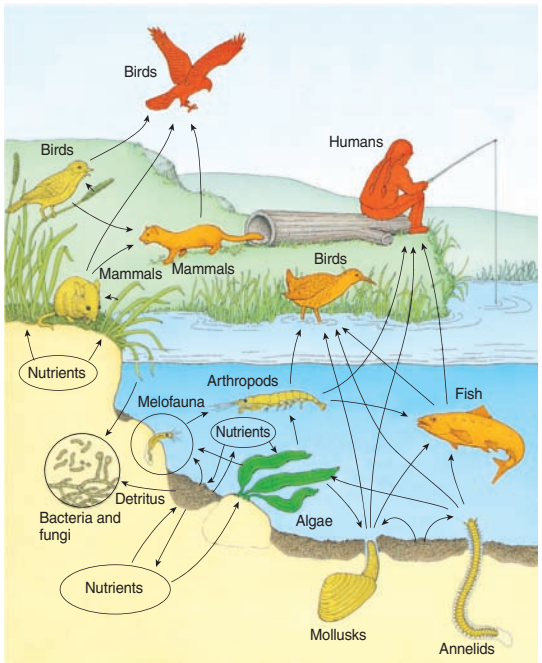
8. Populations that reproduce quickly, produce many offspring but offer little or no parental care, and overshoot the carrying capacity of the environment are called _____.
   a. Malthusian strategists
   b. logistic strategists
   c. type I survivorship curve organisms
   d. type II survivorship curve organisms

9. The reaction in the figure below occurs _____.
   a. only in the presence of oxygen
   b. in the mitochondrion
   c. within the plant chloroplast
   d. in animal cells only



10. Photosynthesis is biochemically related to cellular respiration because _____.
   a. they both require oxygen in order to begin
   b. they both occur in the chloroplast
   c. photosynthesis produces the materials needed for respiration and vice versa
   d. both require ATP and produce sugars

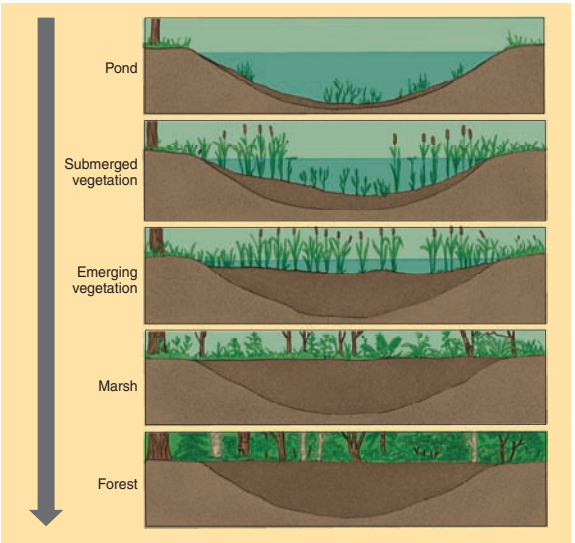
11. The diagram below indicates that if the fish were removed from the food web, _____.
   a. annelids and man would necessarily die out
   b. mollusk and arthropod populations would increase in size
   c. algae would die out
   d. humans would move to a more reliable food source



12. The phosphorus cycle is an example of a(n) _____ cycle.
   a. gaseous
   b. sedimentary
   c. open
   d. exchange pool

13. Water is found in greatest abundance in the _____.
   a. atmosphere
   b. glaciers
   c. rivers and groundwater
   d. oceans

14. The diagram below illustrates the natural process of _____.
   a. ecology
   b. eutrophication
   c. climax community development
   d. deforestation



15. Which of the following activities is most in agreement with the practices of sustainability?
   a. running factories 24 hours a day, 7 days a week to produce more goods
   b. monocultural farming practices
   c. diet practices of a strict vegan-type vegetarian
   d. reducing population growth by closely controlling reproductive behavior

THE PLANNER

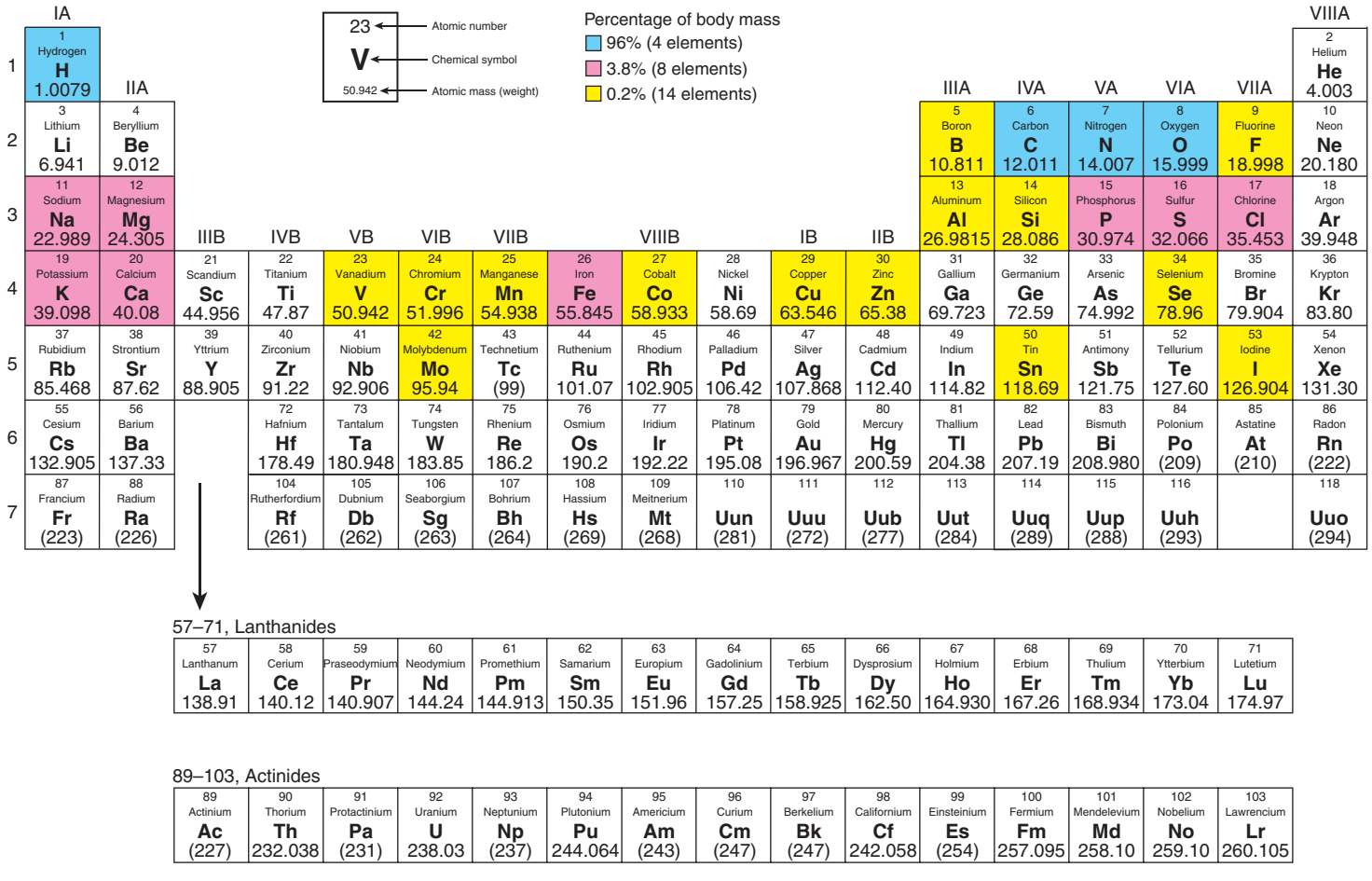
Review your Chapter Planner on the chapter opener and check off your completed work.

Appendix A Periodic Table

The periodic table lists the known **chemical elements**, the basic units of matter. The elements in the table are arranged left to right in rows in order of their **atomic number**, the number of protons in the nucleus. Each horizontal row, numbered from 1 to 7, is a **period**. All elements in a given period have the same number of electron shells as their period number. For example, an atom of hydrogen or helium each has one electron shell, while an atom of potassium or calcium each has four electron shells. The elements in each column, or **group**, share chemical properties. For example, the elements in column IA are very chemically reactive, whereas the elements in column VIIIA have full electron shells and thus are chemically inert.

Scientists now recognize up to 118 different elements; 92 occur naturally on Earth, and the rest (with the exception of element 117) have been produced synthetically using particle accelerators. Elements are designated by **chemical symbols**, which are the first one or two letters of the element's name in English, Latin, or another language.

Twenty-six of the 92 naturally occurring elements normally are present in your body. Of these, just four elements—oxygen (O), carbon (C), hydrogen (H), and nitrogen (N) (coded blue)—constitute about 96% of the body's mass. Eight others—calcium (Ca), phosphorus (P), potassium (K), sulfur (S), sodium (Na), chlorine (Cl), magnesium (Mg), and iron (Fe) (coded pink)—contribute 3.8% of the body's mass. An additional 14 elements, called **trace elements** because they are present in tiny amounts, account for the remaining 0.2% of the body's mass. The trace elements are aluminum, boron, chromium, cobalt, copper, fluorine, iodine, manganese, molybdenum, selenium, silicon, tin, vanadium, and zinc (coded yellow).



Appendix B Measurements

U.S. Customary System

Parameter	Unit	Relation to Other U.S. Units	SI (Metric) Equivalent
Length	inch	1/12 foot	2.54 centimeters
	foot	12 inches	0.305 meter
	yard	36 inches	9.144 meters
	mile	5,280 feet	1.609 kilometers
Mass	grain	1/1000 pound	64.799 milligrams
	dram	1/16 ounce	1.772 grams
	ounce	16 drams	28.350 grams
	pound	16 ounces	453.6 grams
	ton	2,000 pounds	907.18 kilograms
Volume (Liquid)	ounce	1/16 pint	29.574 milliliters
	pint	16 ounces	0.473 liter
	quart	2 pints	0.946 liter
	gallon	4 quarts	3.785 liters
Volume (Dry)	pint	1/2 quart	0.551 liter
	quart	2 pints	1.101 liters
	peck	8 quarts	8.810 liters
	bushel	4 pecks	35.239 liters

International System (SI)

Base Units			Prefixes		
Unit	**Quality**	**Symbol**	**Prefix**	**Multiplier**	**Symbol**
meter	length	M	tera-	10^{12} = 1,000,000,000,000	T
gram	mass	g	giga-	10^{9} = 1,000,000,000	G
second	time	S	mega-	10^{6} = 1,000,000	M
liter	volume	L	kilo-	10^{3} = 1,000	k
mole	amount of matter	Mol	hecto-	10^{2} = 100	h
			deca-	10^{1} = 10	da
			deci-	10^{-1} = 0.1	d
			centi-	10^{-2} = 0.01	c
			milli-	10^{-3} = 0.001	m
			micro-	10^{-6} = 0.000,001	μ
			nano-	10^{-9} = 0.000,000,001	n
			pico-	10^{-12} = 0.000,000,000,001	p

Temperature Conversion
Fahrenheit (F) To Celsius (C)
˚C = (˚F – 32) ÷ 1.8
Celsius (C) To Fahrenheit (F)
˚F = (˚C × 1.8) + 32

U.S. to SI (Metric) Conversion		
When you know	**Multiply by**	**To find**
inches	2.54	centimeters
feet	30.48	centimeters
yards	0.91	meters
miles	1.61	kilometers
ounces	28.35	grams
pounds	0.45	kilograms
tons	0.91	metric tons
fluid ounces	29.57	milliliters
pints	0.47	liters
quarts	0.95	liters
gallons	3.79	liters

SI (Metric) to U.S. Conversion		
When you know	**Multiply by**	**To find**
millimeters	0.04	inches
centimeters	0.39	inches
meters	3.28	feet
kilometers	0.62	miles
liters	1.06	quarts
cubic meters	35.32	cubic feet
grams	0.035	ounces
kilograms	2.21	pounds

Appendix C Answers to Self-Tests

Chapter 1

1b. Has a low degree of organization **2d**. Cell **3b**. B **4c**. A cell **5b**. negative feedback systems **6.** Receptor at top, control center in the middle of the diagram, and effector at the bottom. **7b**. Effector **8a**. Negative feedback **9d**. Chemical level **10a**. Organism level **11d**. D (Letters are the kingdoms and domains of Figure 1.4, listed in order from left to right, Eubacteria to Plantae.) **12b**. Species **13a**. True **14c**. Communicating **15c**. read and evaluate every article that you can find on the subject

Chapter 2

1b. *H. habilis* **2b**. *H. erectus* **3a**. 1 **4b**. they represent the missing link that gave rise to the genus Homo **5a**. True **6d**. All of the above evolved after *H. habilis*. **7b**. False **8a**. 140,000 to 100,000 years ago **9c**. C **10a**. the loss of energy as heat from our bodies **11a**. support and provide movement **12d**. urinary system **13b**. sensory system **14c**. omnivore **15c**. producers

Chapter 3

1e. both c and d **2c**. electron **3a**. positive **4a**. A **5b**. 6 **6c**. polar covalent **7a**. ionic bond **8b**. hydrophilic **9c**. has a high specific heat **10d**. 10,000 units **11a**. carbohydrate **12b**. saturated **13c**. phospholipids **14d**. All of the above are correct. **15c**. Thymine

Chapter 4

1b. Cells cannot arise from preexisting cells. **2b**. a structure within the cytosol that performs at least one vital cellular function **3d**. All of the above are correct. **4a**. True **5d**. Sodium/potassium ATPase **6b**. B **7d**. Allowing cellular interaction with the aqueous environment of the body **8a**. A **9b**. expanding as water moves into the cell **10c**. exocytosis **11d**. Digesting worn-out organelles **12a**. Mitochondrion **13c**. cilia **14b**. Golgi complex **15c**. local hormones

Chapter 5

1c. areolar tissue **2a**. epithelial tissue **3d**. epithelial and some types of connective tissue **4c**. simple epithelium **5b**. a protective membrane **6a**. squamous epithelial cell **7c**. matrix **8b**. hyaline cartilage **9d**. Smooth muscle **10b.** Cardiac muscle **11b**. Dendrites **12c.** tissue, organ, organ system, organism **13a**. Superior **14d**. thoracic cavity **15a**. A

Chapter 6

1c. the ribs **2b**. Sesamoid bones **3b**. epiphysis **4b**. osteoclast **5a**. Male **6a**. synarthrotic joint **7c**. meniscus **8c**. The radius **9b**. B **10d**. carry the impulse to contract quickly through the entire cell **11a**. sarcomere **12c**. contraction **13a**. aerobic pathways **14b**. rectus femoris **15c**. tibia

Chapter 7

1c. the neuron **2a**. afferent division of the PNS **3d**. oligodendrocyte **4b**. sending and receiving motor information **5c**. voltage-gated channel **6a**. –70 mV **7c**. sodium **8b**. absolute refractory period **9e**. Both a and c are correct. **10a**. dura mater **11a**. limbic system **12b**. proprioception **13d**. limbic system **14a**. a highway for information traveling up and down the cord **15b**. increased respiratory and heart rate

Chapter 8

1b. equilibrium **2e**. Both c and d are correct. **3c**. taste bud **4d**. fruity **5a**. To collect and transmit sound **6c**. dynamic equilibrium **7b**. B **8a**. Hearing **9b**. sclera **10e**. Retina **11b**. regulate the amount of light entering the eye **12b**. a convex lens **13b**. False **14d**. ganglionic neurons, bipolar neurons, rods and cones, back of eye **15a**. **and b**. Braille menus and buttons, seeing eye animals

Chapter 9

1d. All of the above are stressors. **2c**. antibodies and immune cells **3a**. the alarm phase **4c**. Dermis **5d**. D **6c**. produce dark pigments to absorb light **7b**. False **8b**. the complement system **9c**. interferon **10b**. False **11d**. Spleen **12d**. All of the above are correct. **13a**. True **14d**. helper T cell **15b**. cytotoxic T cell

Chapter 10

1c. pandemics are worldwide, whereas epidemics are local **2c**. estimate the likelihood of infection among certain groups of individuals **3b**. WHO **4a**. smallpox **5d**. streptococcus **6d**. they have only the cell membrane to carry out complex processes **7d**. All of the above are true of MRSA. **8a**. the black plague **9c**. Tuberculosis **10b**. lysogenic phase **11b**. False **12c**. was found in 125 countries, but has been reduced by a collaborative and global initiative **13a**. WHO has no idea which flu strain will cause the next epidemic **14b**. helper T cell **15c**. fungus

Chapter 11

1c. Abnormal mitochondria **2b**. False **3d**. proto-oncogenes **4a**. In situ **5b**. bacteria **6d**. All of the above are correct. **7c**. radiation and chemicals **8d**. All of the above are correct. **9b**. removing free radicals **10b**. connective tissue **11d**. Blastoma **12c**. colon cancer **13b**. a melanoma **14d**. tumors found within connective and muscular tissues **15a**. immunotherapy

Chapter 12

1b. heart → arteries → capillaries → veins → heart **2c**. D **3d**. I **4a**. True **5b**. ventricular systole **6d**. SA node **7a**. 1 **8b**. slow the impulse to contract and pass it to the AV bundle and on to the ventricles **9c**. vein **10c**. pulmonary arteries carry oxygen-poor blood **11d**. atherosclerosis **12d**. All of the above are correct. **13c**. erythrocyte **14a**. release **15c**. fibrinogen

Chapter 13

1a. warm incoming air **2d**. D **3c**. trachea, bronchi, bronchioles, respiratory bronchioles **4d**. All of the above are correct. **5b**. produce surfactant **6a**. diffusion of gases into and out of the blood **7a**. contracts/increasing **8b**. False **9d**. inspiratory reserve volume **10a**. internal respiration **11b**. the partial pressure of carbon dioxide is lower in the blood **12c**. iron portion of the hemoglobin molecule **13c**. high, high **14a**. True **15b**. tuberculosis

Chapter 14

1c. vitamins **2b**. carbohydrates **3b**. It is indicated as B. **4a**. less, more **5d**. All of the above are correct. **6c**. tips on healthy eating based on your gender, age, and activity level **7b**. False **8c**. A, D, and E **9d**. cellular respiration **10d**. All of the above describe the first reaction shown. **11a**. severe undereating **12a**. in the colon **13d**. Both a and b are correct. **14c**. *Campylobacter* **15c**. when eating top-level predators from a polluted environment

Chapter 15

1a. serosa, muscularis, submucosa, mucosa **2b**. creating the peristaltic wave **3c**. premolars **4c**. liver **5b**. B **6c**. chemical digestion of proteins **7c**. pancreas **8d**. a spiral bacterium **9a**. cephalic phase **10d**. All of the above are true of this organ. **11b**. small intestine; increase surface area **12c**. hepatitis C **13d**. large intestine **14b**. False **15a**. pepsin

Chapter 16

1a. Production of urine **2d**. storage of produced urine **3a**. renal artery → afferent arteriole → efferent arteriole → peritubular capillaries → renal vein **4c**. reabsorb necessary nutrients **5d**. glomerulus **6b**. B and C **7a**. PCT **8d**. too many calcium-rich foods are consumed **9b**. False **10b**. ADH is absent **11c**. aldosterone **12a**. True **13c**. carbon dioxide **14c**. viral infection **15b**. lower level

Chapter 17

1d. All of the above are correct. **2c**. pineal gland **3e**. E **4a**. steroid hormones **5c**. oxytocin **6a**. overproduction of one specific pituitary hormone **7a**. glucocorticoids **8b**. Addison's disease **9d**. blood calcium levels **10a**. pineal gland **11d**. kidney **12c**. maintaining blood volume **13b**. neonate **14c**. infancy **15b**. FSH and LH

Chapter 18

1c. temperature regulation of sperm **2c**. C **3d**. both spermatid and testosterone production **4b**. protect developing spermatids **5d**. seminal vesicles, prostate gland, bulbourethral gland **6a**. seminal vesicles **7b**. stimulate production of sperm **8b**. B **9c**. stimulate secretion of uterine lining **10a**. ovulation **11a**. endometrium **12c**. secondary and mature follicles **13c**. the condom (either male or female) **14b**. surgical methods including vasectomy and tubal ligation **15b**. genital warts

Chapter 19

1d. biochemical changes in the corona radiata **2a**. syngamy **3b**. implantation **4d**. ectoderm, endoderm, and mesoderm **5a**. amnion **6d**. chorion **7c**. digesting maternal endometrium **8d**. round ligament **9b**. False **10b**. second trimester **11a**. positive **12c**. oxytocin **13b**. dilation → expulsion → afterbirth **14d**. external manipulation **15b**. prolactin

Chapter 20

1b. phenotype **2d**. Two of these answers are correct. **3b**. his research was thorough and included quantifiable data **4b**. 3:1 **5a**. True **6b**. 9/16 **7d**. either heterozygous or homozygous dominant **8d**. multifactorial **9b**. DNA is the molecule of inheritance **10c**. transcription/translation **11d**. your likelihood of passing on a deleterious gene to your offspring **12b**. gel electrophoresis **13d**. Restriction fragment-length polymorphism (RFLP) **14d**. create transgenic organisms **15d**. All of the above were stated goals of the project.

Chapter 21

1a. biosphere, ecosystem, community, population, individual **2c**. predator population trends mirror prey population trends, with some delay **3d**. Soil type **4a**. temperate grasslands **5c**. desert **6c**. secondary succession **7b**. False **8a**. Malthusian strategists **9a**. both during the day and at night **10c**. photosynthesis produces the materials needed for respiration and vice versa **11b**. mollusk and arthropod populations would increase in size **12b**. sedimentary **13d**. oceans **14b**. eutrophication **15d**. Reducing population growth by closely controlling reproductive behavior

Glossary

abdominal cavity Cavity that contains stomach, small intestine, spleen, liver, gallbladder, and most of large intestine.
abdominopelvic (ab-dom'-i-nō-PEL-vik) **cavity** Cavity that contains abdominal and pelvic cavities.
absolute refractory period The period of time immediately after an action potential when the neuron is physically incapable of beginning a second action potential while membrane channels are reset to their original position.
acetylcholine (as'-ē-til-KŌ-lēn) **(ACh)** Common neurotransmitter used to signal muscle contraction.
acetylcholinesterase An enzyme found in neuromuscular junctions and in neuron synapses that quickly breaks down acetylcholine, preventing continuous stimulation of the postsynaptic cell.
acid rain Acidic precipitation caused by the sulfur- and nitrogen-oxide pollution that combine with water in the atmosphere.
acidosis Acidic condition in the blood.
acquired immunodeficiency syndrome (AIDS) A fatal disease caused by the human immunodeficiency virus (HIV). Characterized by a positive HIV-antibody test, low helper T cell count, and certain indicator diseases. Other symptoms include fever or night sweats, coughing, sore throat, fatigue, body aches, weight loss, and enlarged lymph nodes.
acromegaly (ak-rō-MEG-al-ē) The secretion of excess growth hormone after the closure of the epiphyseal plates in the long bones.
acrosome (AK-rō-sōm) A vesicle on the point of the sperm head that contains digestive enzymes.
actin (AK-tin) Protein that functions in muscle contraction; see *myosin*.
active transport Movement of a molecule or ion through the cell membrane, against the concentration gradient.
acute (a-KYOOT *or* a-KUTE) Having rapid onset, severe symptoms, and a short course; not chronic.
acute sinusitis Inflammation of the sinuses with sudden onset and usually of short duration.
adaptive radiation Creation of several species from one ancestor that reaches habitat with empty niches.
Addison's disease The hyposecretion of glucocorticoids and aldosterone, usually due to autoimmune destruction of the adrenal cortex.
adenosine diphosphate (a-DEN-ō-sēn dī-FOS-fāt) **(ADP)** The molecule that results when ATP releases one phosphate group.
adenosine triphosphate (ATP) The primary energy molecule that can be used to perform cellular functions.
adhesive Having the ability to stick to other surfaces.
adipocytes Specialized cells (fat cells) that store large quantities of lipid.
adrenocorticotropic (ad-rē'-nō-kor-ti-kō-TRŌP-ik) **hormone (ACTH)** A hormone produced by the anterior pituitary that influences the production and secretion of certain hormones of the adrenal cortex.
aerobic pathway Metabolic pathway that requires oxygen to burn glucose completely.
aerobic Requiring oxygen to metabolize.
afferent (AF-er-ent) Moving toward the main organ; often refers to sensory impulses moving toward the brain (neurons that carry information toward the CNS).
affinity An attraction between particles that increases chances of their combining.
afterbirth (placental stage) Stage of delivery when the placenta is released and expelled.
agarose A gel-like compound obtained from agar that provides a flexible, yet solid, medium for separation of DNA fragments.
agglutinate (a-GLOO-ti-nāte) To clump with other cells due to the adhesion of surface proteins.
agglutinin (a-GLOO-tin-in) Agent that causes cells to clump together or agglutinate.
agonist (AG-ō-nist) The muscle in an antagonistic pair that shortens during a specific movement; prime mover.
aldosterone (al-DOS-ter-ōn) Hormone that affects water balance by regulating sodium and potassium excretion.
allantois (a-LAN-tō-is) An outpouching of the yolk sac that is an early site for blood formation and development of the urinary bladder.
alleles (a-LEELZ *or* a-LĒLZ) Genes found on the same spot on the same chromosome in different individuals, coding for subtle variations of the same protein.
alpha helix Spiral chain of monomers, resembling an old-fashioned telephone cord.
altruistic Putting the needs of others ahead of, or equal to, personal needs.
alveolar macrophages (MAK-rō-fāj-ez) **(dust cells)** In alveoli, immune cells that remove any inhaled particles that escaped the mucus and cilia of the conducting zone.
alveolar sac A cluster of alveoli that share a common opening.
alveolus (al-VE-ō-lus) A small hollow or cavity; an air sac in the lungs; milk-secreting portion of a mammary gland. Plural is *alveoli* (al-VE-ol-ī).
amenorrhea (ā-men-ō-RE-a) Absence of menstruation.
amino acids The building blocks of proteins.
aminopeptidase Secreted from the edges of the intestinal cells, this enzyme digests proteins.
amniocentesis The collection of a small amount of amniotic fluid for analysis for genetic defects.
amnion (AM-nē-on) Extraembryonic membrane that lines the amniotic cavity, providing a diffusion area for the amniotic fluid.
amniotic cavity The fluid-filled cavity that bathes the developing embryo and fetus.
amoeba A single-celled organism that moves using pseudopods (false feet formed by oozing a portion of the body forward).
amphiarthrotic Describes a joint that is partly movable.
anabolic steroids Lipid-soluble cholesterol-based compounds that stimulate increased muscle development, among other effects.
anabolism (a-NAB-ō-lizm) The building up of larger molecules from smaller ones (contrast to catabolism).
anaerobic (an-ar-Ō-bik) Metabolism that occurs without oxygen present.
anaerobic pathways Metabolic pathways that occur in the cytoplasm and burn glucose to lactic acid, releasing some energy.
anastomoses (a-nas-tō-MŌ-sēz) Networks or connections between two or more vessels.
anatomical position Human body arranged in standard position; used to describe location of parts.
androgens (AN-drō-jenz) Masculinizing sex hormones produced by the testes in males and the adrenal cortex in both sexes; responsible for libido.
anemia (a-NĒ-mē-a) Condition of the blood in which the number of functional red blood cells or their hemoglobin content is below normal.
aneurysm (AN-ū-rizm) Usually fatal, a condition that occurs when a blood vessel wall balloons under pressure, forming a weak spot that can be burst by the increased blood pressure generated with each heartbeat.
angina pectoris (an-JĪ-na *or* AN-ji-na PEK-to-ris) A pain in the chest related to reduced coronary circulation due to coronary artery

disease (CAD) or spasms of vascular smooth muscle in coronary arteries.

angiogenesis The growth of new networks of blood vessels (*angio* = blood vessel; *genesis* = new creation).

animalia The kingdom of life that includes animals.

anorexia nervosa A disorder characterized by severely limiting caloric intake; symptoms include osteoporosis, brittle hair, intolerance of cold, and muscle wasting.

antagonist (an-TAG-ō-nist) The muscle in an antagonistic pair that lengthens during a specific movement.

antagonistic (an-tag-ō-NIST-ik) **pair** Muscles with opposite actions working together to provide smooth and controlled movements; *synergistic pair.*

antibiotics Drugs that interfere with cellular processes in bacterial cells.

antibodies (AN-ti-bod'-ēz) Proteins produced by lymphocytes and directed against specific pathogens or foreign tissue.

anticodon Three bases on tRNA, carrying the same information as a codon.

antidiuretic (an'-ti-dī-ū-RET-ik) **hormone** Hormone that prevents water loss by altering the permeability of the distal convoluted tubule cells to water.

apical membrane Membrane at the free end, or top, of the intestinal cells.

apneustic (ap-NOO-stik) A part of the respiratory center in the pons that stimulates deep, gasping breathing.

apocrine (AP-ō-krin) A cellular secretion that pinches off the upper portion of the cell with the secretion.

apoptosis (ap-ō-TŌ-sis *or* ap'-ōp-TŌ-sis) Programmed cell death.

appendicitis A blockage in the appendix that prevents normal flow through the large intestine, leading to a buildup of pressure, decreased blood flow, and inflammation.

appendicular skeleton System of appendages: limbs, pelvic girdle, and shoulders.

appositional growth Growth at the outer surface of bone.

aqueous (AK-wē-us) Solution of material dissolved in water.

aqueous humor (AK-wē-us HŪ-mer) The watery fluid, similar in composition to cerebrospinal fluid, that fills the anterior cavity of the eye.

aquifer A large body of groundwater.

arachnoid (a-RAK-noyd) The middle of the three meninges (coverings) of the brain and spinal cord.

archaebacteria Single-celled organisms, considered the most ancient forms of life; the kingdom that includes them.

arterioles (ar-TE-rē-ōl) A small, almost microscopic, artery that delivers blood to a capillary.

artery (AR-ter-ē) A blood vessel that carries blood away from the heart.

articulates Joins; an articulation is a joint holding two bones together.

articulating cartilage (KAR-ti-lij) Hyaline cartilage that prevents bones from grinding against each other.

arytenoid (ar'-i-TE-noyd) **cartilages** A pair of small, pyramidal cartilages of the larynx that move the vocal folds.

association area Areas of the brain that integrate new information with previously stored information, associating new and old information.

asthma (AZ-ma) A constrictive pulmonary disease that can be life threatening.

asymptomatic Without symptoms.

atherosclerosis (ath'-er-ō-skle-RŌ-sis) (literally "hardened vessels") Disease of the blood vessels wherein plaques of fatty compounds are deposited in the artery lumen, slowing blood flow.

atom The smallest unit of an element that has the properties of that element.

atomic mass The total weight of neutrons and protons of an atom; different isotopes have different atomic masses.

atomic number The number of protons in the nucleus of an atom.

atresia (a-TRE-zē-a) Reabsorption of immature ova prior to birth.

atria (Ā-trē-a) Small, thin-walled chambers sitting atop the thick-walled, muscular ventricles in the heart.

atrioventricular (AV) (ā'-trē-ō-ven-TRIK-ū-lar) **bundle** The part of the conduction system of the heart that begins at the atrioventricular (AV) node, passes through the interventricular wall, then extends a short distance down the interventricular wall before splitting into right and left bundle branches.

atrioventricular (AV) **node** The part of the conduction system of the heart made up of a compact mass of conducting cells located in the wall between the two atria.

Attention Deficit Hyperactivity Disorder (ADHD) A disorder in which behaviors are uncontrolled, resulting in impaired learning.

attenuated Reduced capability of a pathogen to cause disease.

auditory canal The hole that leads from the pinna to the tympanic membrane through which sound waves pass.

autoimmune Type of immune response launched against healthy tissues, destroying normal organs.

autonomic (aw'-tō-NOM-ik) **division** Division of the nervous system regulating functions, such as blood vessel diameter and stomach activity.

autonomic division (ANS) Division of the nervous system regulating functions, such as blood vessel diameter and stomach activity.

autosomal Any chromosome other than the sex chromosomes, X and Y

autotroph Organism that can make its own food, usually through photosynthesis.

avascular (Ā-vas'-kū-lar) Without blood vessels.

axial skeleton Bone structures parallel to the body's core; head, vertebrae.

axillary nodes Lymph nodes located in the armpit.

bacteriolytic Type of agent that lyses or destroys bacteria.

balloon angioplasty (an'-jē-ō-PLAS-tē) Medical procedure in which a balloon is inserted into an atherosclerotic artery. The tip inflates, flattening the plaque, to improve blood flow.

basal metabolic rate Rate of energy use when the body is quiet, resting, and fasting.

basophil (BĀ-sō-fil) A white blood cell with a pale nucleus and large granules that stain blue-purple with basic dyes.

bicarbonate ion HCO_3^-, a buffering ion.

biceps brachii (BRĀ-kē) The anterior muscle of the upper arm.

bicuspid (bī-KUS-pid) The valve between the left atrium and left ventricle, composed of two opposing cusps or flaps of connective tissue.

bile Compound formed by the liver as a byproduct of the breakdown of hemoglobin and cholesterol.

biodiversity A measure of species richness in a location.

biogeographic range The expected geographical range of an organism, based on its habitat requirements.

biomagnification The concentration of toxins as they move up the food chain.

biome A regional community characterized by a dominant plant life and climate.

biosphere The Earth's land, water, and air, plus all life.

biotic community All the organisms in particular location or relationship.

biotic potential The maximum growth rate of a population under ideal conditions.
bipedal Two-footed rather than four-footed; walks on two feet.
blastocyst (BLAS-tō-sist) The stage of development where cellular specialization begins.
blastomere (BLAS-tō-mēr) Small cell created during the rapid cell division of cleavage.
blastula (BLAS-tyū-la) An early stage in the development of a zygote.
bleached Fallen apart, as in rhodopsin that has decomposed and cannot recombine.
blood The fluid that circulates through the heart, arteries, capillaries, and veins and that constitutes the chief means of transport within the body.
blood–brain barrier A barrier consisting of specialized brain capillaries and astrocytes that prevents the passage of materials from the blood to the cerebrospinal fluid and brain.
bolus (BŌ-lus) A round, soft mass of chewed food within the digestive tract.
bolus A round, soft mass of chewed food within the digestive tract.
bottleneck effect Drastic reduction in species population; it reduces diversity of species genes.
brain The part of the central nervous system within the cranial cavity.
Broca's (BRŌ-kaz) **area** Motor area of the brain in the frontal lobe that translates thoughts into speech.
bronchi (BRON-kē) Branches of the respiratory passageway including primary bronchi, and divisions of the primary bronchi that are distributed to the lobes of the lung. Singular is *bronchus*.
bronchial tree The trachea, bronchi, and their branching structures up to and including the terminal bronchioles.
bronchiole (BRONG-kē-ōl) Smaller division of a tertiary bronchus giving rise to terminal bronchioles and then respiratory bronchioles that deliver air to the alveolar sacs.
bronchitis An inflammation of the mucous membrane lining the bronchi.
bronchodilator Inhalant that relaxes the smooth muscle of the bronchi, opens the constricted tubes, and helps clear unwanted mucus.
bronchopulmonary (brong'-kō-PUL-mō-ner-ē) **segment** One of the smaller divisions of a lobe of a lung supplied by its own branches of a bronchus.
brush border Entire surface of a cell covered with microvilli.
buffer A compound that absorbs hydrogen ions or hydroxide ions, stabilizing pH.
bulbourethral (bul'-bō-ū-RE-thral) **gland** One of a pair of glands inferior to the prostate that secretes alkaline fluid into the urethra.
bulimia (boo-LIM-ē-a *or* boo-LĒ-mē-a) **nervosa** A disorder characterized by overeating at least twice a week, followed by purging by self-induced vomiting, strict dieting or fasting, vigorous exercise, or use of laxatives or diuretics. Also called binge purge syndrome.
bursa (BUR-sa) Fluid-filled sac between the bones or tendons of a joint and the skin, positioned to reduce friction.
bypass surgery Heart surgery that bypasses clogged arteries of the heart. These bypasses are looped over the damaged coronary artery and sewn in place so blood can flow around the damage and continue to nourish the heart tissue.

calcium oxalate A chemical compound composed of calcium ions bound to the oxalate ion ($C_2O_4^{2-}$).
callus Thickened formation on bone in response to wear.
calorie A measure of the amount of heat stored in food. One calorie is the amount of heat needed to raise the temperature of 1 kilogram of water 1 degree Celsius.
canaliculi (kan'-a-LIK-ū-lī) Canals that connect cells in ossified bone. Singular is *canaliculus*.
capacitated Activated; that is, capable of fertilizing an ovum.
capacitation (ka'-pas-i-TĀ-shun) Changes that make sperm able to fertilize an egg.
capillaries (KAP-i-lar'-ēz) Very small diffusion vessels located between an arteri-ole and a venule.
capillary bed Interwoven mat of capillaries threading through a tissue.
carbaminohemoglobin Carbon dioxide bound to the protein portion of hemoglobin.
carbohydrates The most efficient source of energy for humans; molecules composed of carbon, hydrogen, and oxygen in a 1:2:1 ratio.
carbon monoxide (CO) A molecule composed of one atom of carbon and one atom of oxygen, covalently bound.
carbonic anhydrase Enzyme that allows red blood cells to remove most of the carbon dioxide from the blood.
carboxypeptidase Pancreatic enzyme that digests proteins.
carcinogenesis The process by which cancer develops.
carcinogens Environmental agents that can cause cancer.
carcinoma Cancer of the epithelial tissue.
cardiac sinus Large vein on the dorsal surface of the right atrium that collects blood from the cardiac veins and returns it to the chambers of the heart.
cardiovascular system The system that consists of the heart, veins, blood vessels, and blood. It transports blood, carrying nutrients, wastes, and dissolved gases to and from the tissues.
carina Extremely sensitive area where the trachea divides into the left and right primary bronchi, at the lower base of the trachea.
carnivore (secondary consumer) Animal that eats other animals.
carotene A yellow-orange pigment.
carrying capacity The number of individuals in each population an area can support in a sustainable manner.
cartilage (KAR-ti-lij) A type of connective tissue consisting of chondrocytes in lacunae embedded in a dense network of collagen and elastic fibers.
casts Small structures formed by mineral or fat deposits on the walls of the renal tubules.
catabolism (ka-TAB-ō-lizm) Metabolic activity that breaks down tissue.
CD4 Recognition elements in major histocompatibility complex (MHC) class II immune responses; identifies certain T cells.
cell division Process by which a cell reproduces, includes nuclear division (mitosis) and cytoplasmic division (cytokinesis).
cell The smallest unit of life, contained in a membrane or cell wall.
cell theory Overall understanding of the role of cells in biology.
cellulite Adipose tissue dimpled by differential expansion of connective and lipid components.
cellulose Insoluble carbohydrate that provides structure to plant cells.
central nervous system (CNS) That portion of the nervous system that consists of the brain and spinal cord.
central vacuole Container inside plant cells that maintains turgor.
centrifugation Rapid spinning of a sample to separate components by density.
cephalic (se-FAL-ik) **phase** In digestion, the initial phase consisting of reflexes initiated by the senses.
cerebral edema Fluid accumulation in the brain or cerebral area.

cerebrospinal fluid (CSF) A liquid similar to plasma, but with less dissolved material, that maintains uniform pressure within the brain and spinal cord.
cerebrum (SER-e-brum *or* se-RĒ-brum) The two hemispheres of the forebrain, making up the largest part of the brain.
cervical nodes Lymph nodes located in the neck.
cervix Base of the uterus.
cGMP Cyclic guanine monophosphate, an energy molecule.
chemical digestion The breaking down of food using enzymes that alter the chemical structure of the food.
chemically regulated Describes membrane channels that open or close in response to a specific chemical, such as sodium.
chemiosmosis The diffusion of hydrogen ions across a membrane, generating ATP as the ions move from high to low concentrations.
chemoreceptors Sensory receptors that detect small changes in levels of specific chemicals, such as carbon dioxide.
chloride shift An exchange reaction that requires no ATP because it merely switches the positions of the anions.
chlorofluorocarbons Compounds made of hydrogen, carbon, fluorine, and chlorine, once used as refrigerants.
chlorophyll A blue-green photopigment found in plants and algae.
chloroplast Green organelle in plants that contains chlorophyll.
cholecystokinin (kō′-lē-sis-TO-kīn-in) **(CCK)** Hormone that inhibits stomach emptying.
cholesterol A class of steroids found in animals; aids in membrane fluidity.
chondroblasts Immature cartilage cells, not yet completely surrounded by the cartilage matrix.
chondrocyte (KON-drō-sīt) Cartilaginous cell secreting a gel-like matrix that eventually surrounds and imprisons it.
chordae tendineae (KOR-dē TEN-di-nē-ē) (literally chords of tendons) The "heart strings" that anchor the cusps of the valves to the papillary muscles.
chorion (KŌ-rē-on) Tissue that forms the exchange membrane between fetal and maternal blood.
chorionic villi (kō-rē-ON-ik VIL-lī) Finger-like extensions of the chorion that protrude into the endometrial lining.
choroid (KŌ-royd) One of the vascular layers of the eyeball that carries the blood supply and the melanin of the inner eye.
chromatin (KRō-ma-tin) Thread-like material that packages DNA.
chromosome (KRO-mō-sōm) Genetic material consisting of multiple genes strung end to end.
chronic (KRON-ik) Long-term or frequently recurring; applied to a disease.
chronic obstructive pulmonary disease (COPD) Emphysema or chronic bronchitis, a disease that severely obstructs airflow.
chronic sinusitis Inflammation of the sinuses that persists for long periods of time.
chylomicrons Small lipoproteins carrying ingested fat from the intestinal mucosa to the liver.
chyme The thick, partially digested fluid in the stomach and small intestine.
chymotrypsin Pancreatic enzyme that digests proteins.
cilium (SIL-e-um) Hair-like appendage of a cell, used to move extracellular fluid. Plural is *cilia*.
circadian rhythm A daily predictable physiologic cycle based on a 24-hour day.
cirrhosis (si-RŌ-sis) Scar tissue buildup in the liver generally caused by alcohol consumption, chronic hepatitis infection, autoimmune diseases that attack the liver, or congenital defects.
class A taxonomic subcategory of phyla.
class II MHC (major histocompatibility complex) Recognition proteins present on the membranes of antigen-presenting cells and lymphocytes.
cleavage Repeated cell divisions with little time between rounds to enlarge the resulting daughter cells.
climax community Relatively stable, mature community that has reached equilibrium after passing through a series of established steps.
clitoris (KLI-to-ris) An erectile organ of the female external genitalia that is homologous to the penis.
codominant Neither form of a gene will overshadow the other; when both forms are present, the individual will express both equally.
codon Three bases on mRNA, corresponding to one amino acid.
cohesive Having the ability to stick to itself.
cohort A group of organisms sharing a particular characteristic.
collagen (KOL-a-jen) Group of tough molecules often found in connective tissue.
colon The portion of the large intestine consisting of ascending, transverse, sigmoid, and descending portions.
colony-stimulating factors Blood-borne compounds that cause cells in the bone marrow to produce new blood cells.
colostrum (kō-LOS-trum) The first substance produced by the mammary gland, a watery fluid rich in proteins and antibodies.
columnar epithelium Tissue composed of cylindrical epithelial cells.
community diversity A measure of the diverse forms of life in a community.
community Group of interacting organisms.
complement system A series of plasma proteins that, when activated, associate in a specific order to destroy pathogenic bacteria.
compound Molecule composed of at least two elements.
conducting zone Portion of the respiratory tract that conducts air to the respiratory membrane.
conduction deafness Deafness resulting from poor conduction of sound to the inner ear.
congenital (kon-JEN-i-tal) A condition that is present at birth, because of genetic or environmental factors; usually detrimental.
congenital hypothyroidism Glandular defect that can lead to mental retardation and stunted bone growth.
congestive heart failure A condition in which the heart weakens to the point that it cannot push the blood through the circulatory system. Blood builds up in the lungs, causing difficulty breathing.
connective tissue Stretchy, strong tissue that connects body structures, providing support.
constipation Difficult or infrequent defecation, leading to dry, potentially painful fecal evacuation.
constrictive In the respiratory system, indicates narrowing of the airways.
consumers Organisms that must ingest organic compounds as nutrients because they cannot manufacture their own.
contraceptive Chemical, anatomical or physical modification that prevents pregnancy.
convergent evolution Evolution of similar structures in unrelated organisms.
cornea (KOR-nē-a) The nonvascular, transparent fibrous coat on the front of the eye.
corona radiata The inner layer of granulosa cells around a secondary oocyte.
coronary arteries Arteries that supply oxygen and nutrients to cardiac muscle.
coronary sinus A wide venous channel on the back of the heart that collects the blood from the coronary circulation and returns it to the right atrium.

corpus albicans (KOR-pus AL-bi-kanz) A white fibrous patch in the ovary that forms after the corpus luteum regresses.
corpus luteum (LOO-t ē-um) Spent follicular cells on the ovary.
cortex (KOR-teks) Thin outer layer of any organ.
cortisol Secretion of the adrenal cortex that suppresses immune system, raises blood pressure, and raises blood glucose.
cortisol-releasing hormone A compound secreted by the hypothalamus into the portal system causing release of ACTH, a pituitary hormone.
countercurrent multiplication (CCM) Mechanism that increases the diffusion rate by flowing solutions in opposite directions on either side of a diffusion membrane.
covalent bond Relatively weak bond between atoms, made by sharing electrons.
cranial cavity Cavity that contains the brain.
cranial nerves Twelve pairs of nerves that leave the brain and supply sensory and motor neurons to the head, neck, part of the trunk, and viscera of the thorax and abdomen. Each is designated by a Roman numeral and a name.
cranium Brain case, or skull.
creatine phosphate Compound that stores energy during anaerobic metabolism in muscle cell.
creationism Belief in a literal interpretation of the Biblical story of the creation of the universe, the Earth, and life.
cribriform plate A fragile, porous area of the ethmoid bone at the superior portion of the nasal cavity.
cricoid cartilage The only complete ring of cartilage in the respiratory system, it is narrow in front but thick in the back of the larynx.
cristae Folds of a membrane inside mitochondria.
cross-pollinating Fertilizing the ovum of a flower with pollen from a different plant.
cuboidal epithelium Tissue composed of cube-shaped epithelial cells.
cupula (KŪpū-la) A mass of gelatinous material covering the hair cells of a crista; a sensory receptor in the ampulla of a semicircular canal stimulated when the head moves.
Cushing's syndrome Condition caused by a hypersecretion of adrenal cortex hormones, characterized by spindly legs, "moon face," "buffalo hump," pendulous abdomen, flushed facial skin, poor wound healing, hyperglycemia, osteoporosis, hypertension, and susceptibility to disease.
cutaneous Of or pertaining to the skin.
cyanobacteria Blue-green, photosynthetic bacteria.
cyclic AMP (cAMP) A form of adenosine monophosphate in which the phosphate appears in ring formation, carrying little energy (not enough to harness for metabolic processes).
cystic fibrosis (CF) Congenital disease causing thick mucus in the lungs.
cytokines Chemical signals released by immune cells during the immune response.
cytology The study of cells. A cytologist is a scientist who studies cells.
cytoskeleton The internal framework of a cell.
cytotoxic T cells Subset of T lymphocytes responsible for killing virally infected cells.

dalton A unit of mass, equal to the mass of one proton.
Dalton's law Law stating that gases move independently down their pressure gradient, toward lower pressure.
decomposer (detritivore) Organism that feeds upon dead organisms and returns nutrients to the soil.
deductive reasoning Method of reasoning that moves from the general hypothesis to a specific situation.
defecation (def-e-KĀ-shun) The discharge of feces from the rectum.
deglutition (dē-gloo-TISH-un) The act of swallowing.
dentin Bony tissue that lies below the enamel, inside the tooth.
dentrification The conversion of nitrates into nitrogen gas.
depolarizing Altering the neuron transmembrane potential so a weaker stimulus can begin an action potential.
dermis The underlying, vascularized, connective tissue layer of the skin.
detritus Loose fragments of organic and inorganic matter obtained from decomposition and weathering.
dialysis Substance exchange via diffusion across a membrane, artificially mimicking the kidney.
diapedesis A process by which macrophages escape the bloodstream by squeezing between cells of the vessel wall.
diaphysis dī-AF-i-sis) Shaft of a long bone.
diarrhea (dī-a-RE-a) Frequent defecation of liquid feces caused by irritation of the colon.
diarthrotic Fully movable, describing a joint.
diastole Relaxation of the heart.
differentiation Cellular process that causes the cell to become specialized to perform a particular function.
diffusion Movement from a region of higher concentration to a region of lower concentration.
dihydrotestosterone (DHT) Male sex hormone that works with testosterone to grow and develop male reproductive organs, secondary sex characteristics, and the body.
dilation The act of expanding or being expanded.
dipeptidase Secreted from the edges of the intestinal cells, this enzyme digests proteins.
diploid Having the total number of chromosomes of the body cells, twice that of the gametes.
dissociation Separation of the strands of DNA.
distal (DIS-tal) Farther from the attachment of a limb to the trunk (the core of the body); farther from the point of origin or attachment; opposite of *proximal*.
divergent Separating from a common point; growing farther apart.
DNA fingerprint Process of identifying individuals based on their genetic sequences.
DNA primer A short segment of DNA binding to the original DNA strand, initiating DNA replication.
DNA sequence The sequence of bases (adenine, cytosine, thymine, and guanine) on a chromosome.
DNA sequencing Determining the sequence of A, C, T, and G on a gene or chromosome.
dominant Describes an allele of a gene that determines phenotype even if only one such allele is present.
dominant population The population with the largest number of individuals in an area.
dorsal root The sensory neurons of each spinal nerve that split off and enter the spinal cord from the posterior (dorsal) surface.
downregulated Slowed down, as in a slowed-down cellular function.
ductus deferens (vas deferens) The duct that carries sperm from the epididymis to the ejaculatory duct.
duodenum (doo'-ō-DE-num *or* doo-OD-e-num) Region of the small intestine, extending about 25 cm from the pyloric sphincter.
dura mater (DOO-ra MĀ-ter) The outermost of the three meninges (coverings) of the brain and spinal cord.
dysentery Severe diarrhea accompanying swelling and bleeding of the lower bowels.

early embryonic Pertaining to the period from fertilization to implantation in the first two weeks; also known as pre-embryonic.

eccrine (EK-rēn) Describes a secretion that does not include any portion of the secreting cell.
ecology The study of the relationships among and between living and nonliving portions of the environment.
ecosystem A subdivision of the biosphere.
ectoderm The outer cell layer in the embryo.
ectopic (ek-TOP-ik) **pregnancy** Pregnancy in which the embryo is implanted outside the uterus.
edema (e-DE-ma) Abnormal swelling in tissues.
efferent Away from an organ; in the nervous system, neurons that carry information away from the CNS.
elastase Pancreatic enzyme that digests proteins.
elastin Springy type of connective tissue.
elective abortion Removal of the developing embryo initiated by personal choice.
electrocardiogram A graphic representation of the electrical conditions during a heartbeat.
electrolytes Compounds that form a solution that can conduct electricity.
electron The negative particle in the atom, found in orbitals surrounding the nucleus.
electron transport chain Step three in aerobic respiration, wherein electrons are passed along in a series of chemical reactions, eventually producing ATP.
element A substance made entirely of one type of atom; it cannot be chemically broken down.
embolism (EM-bō-lism) A blood clot, bubble of air or fat from broken bones, mass of bacteria, or other debris or foreign material floating in the blood.
embryonic Pertaining to the period from the end of the second week through the eighth week of development.
emigration Departure from a location.
emphysema (em-fi-SE-ma) A lung disorder in which alveolar walls disintegrate, producing abnormally large air spaces and loss of elasticity in the lungs.
endemic Found only in one area; native to a region rather than introduced.
endocardium (en-dō-KAR-dē-um) The inside lining of the heart wall, it covers the valves and tendons that hold the valves open.
endochondral (en'-dō-KON-dral) Within cartilage.
endocytosis (en'-dō-sī-TŌ-sis) Movement of compounds into a cell.
endoderm The innermost embryonic cell layer.
endometriosis (en'-dō-ME-trē-ō'-sis) The growth of endometrial tissue outside the uterus.
endometrium (en'-dō-ME-trē-um) The mucous membrane lining the uterus.
endomysium (en'-dō-MĪZ-ē-um) The innermost connective tissue lining, on top of the muscle cell membrane.
endoplasmic reticulum (en'-dō-PLAS-mik re-TIK-ū-lum) A type of organelle; see rough *endoplasmic reticulum* or *smooth endoplasmic reticulum*.
endorphins and **enkephalins** Naturally occurring compounds that reduce the sensation of pain and produce a feeling of well-being.
endothermic Describes organisms that maintain an internal temperature within a narrow range despite environmental conditions.
energy Usable heat or power.
eosinophil (ē-ō-SIN-ō-fil) A type of white blood cell characterized by granules that stain red or pink with acid dyes.
epidemic Disease outbreak.
epidermis The outermost, nonvascular layer of the skin.
epididymis (ep'-i-DID-i-mis) Storage area and final maturation center in the testes, for spermatozoa.
epiglottis Large, leaf-shaped piece of cartilage lying over the top of the larynx.
epimysium (ep-i-MĪZ-ē-um) The outermost covering on a muscle, separating one muscle from the next.
epinephrine A hormone released from the adrenal gland in response to stress.
epiphyseal plate (ep-i-FIZ-ē-al) Area of cartilage where long bones grow during childhood and adolescence.
epiphysis (e-PIF-i-sis) End of a bone.
epithelial (ep-i-THE-lē-al) **tissue** Tissue that covers the body, lines all cavities, and composes the glands.
erythrocytes Red blood cells.
erythropoiesis The formation of red blood cells (*erythro* = red; *poiesis* = to form).
esophagus (e-SOF-a-gus) The hollow muscular tube that connects the pharynx and the stomach.
essential amino acids Eight amino acids that must be consumed by humans, since the body does not manufacture them.
estrogens (ES-tro-jenz) Feminizing sex hormones produced by the ovaries; govern development of oocytes, maintenance of female reproductive structures, and secondary sex characteristics.
ethical decision A decision based on the principles of right and wrong, rather than on financial, personal, or political gain.
eubacteria Single-celled organisms without nuclei; the kingdom that includes them.
eukaryotic Cell that contains a distinct membrane-bound nucleus.
eustachian (ū-STA-shun *or* ū-STA-kē-an) **tube** The tube that connects the middle ear with the nose and nasopharynx region of the throat.
eutrophying Encouraging blooms of plants and algae that eventually deplete the resources of a body of water, leading to the destruction of that ecosystem.
evaporates Changes from a liquid to a vapor through the addition of energy.
evolution Descent with modification.
exchange pool Area where a chemical resource is in a form that the biotic community can use.
excitatory postsynaptic potentials (EPSPs) A stimulus that moves the postsynaptic neuron membrane potential closer to threshold, without causing an action potential.
exhalation The act of decreasing lung volume, expelling air.
exocrine (EK-sō-krin) **glands** Glands that secrete directly into ducts.
exocytosis (ex'-ō-sī-TŌ-sis) Movement of compounds out of a cell.
exophthalmos (ek'-sof-THAL-mas) Fluid buildup behind the eyes, may cause the eyes to "pop" from their sockets.
exothermic (ex'-ō-THER-mik) Chemical reaction that releases energy.
expiratory reserve volume (ERV) Additional volume of air that can be expelled from the lungs after a normal exhalation: 700 ml for females, 1000 ml for males.
expulsion The act of forcing out.
extension Condition of diarthrotic joint where the joint angle is maximal; contrast with flexion.
external nares (NĀ-rez) The nostrils themselves, the paired openings into the nasal cavity.
external respiration The exchange of gases between the air in the alveoli and the blood in the respiratory capillaries.
external sphincter muscle Ring of voluntary skeletal muscle that closes the urethra.
extinction Death of an entire species, often due to some combination of predation, habitat destruction, and disease.
extraembryonic Outside of the cells of an embryo.
extrinsic controls The hearbeat control used to modulate the intrinsic baseline rate to meet the body's immediate demands.

facilitated diffusion Movement of substances across a membrane from high concentration to low with the assistance of a carrier molecule.
fallopian (fal-LŌ-pē-an) **tube** (uterine tube) Duct that transports ova from the ovary to the uterus.
family A taxonomic subcategory of order.
fast block Depolarization of the oocyte membrane immediately after syngamy.
fast-twitch fiber Myofibril that contracts quickly.
feedback system System whose effects change its own rate.
fenestrations Windows or openings between cells in the lining of the glomerulus.
fetal Pertaining to the period from beginning of week 9 through birth.
fever State of hyperthermia, usually a sign of disease.
fiber Undigestible carbohydrate fibers that pass through the digestive tract without releasing any stored energy.
fibrin A thread-like protein formed by platelets during clot formation.
fibrocartilage Cartilage with strengthening fibers in the matrix.
filtration Process that removes some solids from a liquid.
fitness The relative ability of an individual to produce viable (living) offspring that survive to reproduce (and pass on DNA).
fixing Converting gaseous elements to organic compounds.
flagellum (fla-JEL-um) Whip-like appendage to cell, used for movement, found on sperm. Plural is *flagella* (fla-JEL-a).
flexion (FLEK-shun) State of a diarthrotic joint where the angle at the joint is minimal; contrast with extension.
follicle stimulating hormone (FSH) A hormone that stimulates the growth and functioning of the ovaries and testes.
follicle A small cavity or cul-de-sac; hair originates in a hair follicle.
follicular cells Cells stimulated to develop alongside the oocyte.
food chain System of energy transfer that starts with green plants and moves upward through various trophic levels to top carnivores.
fossa A pit, groove, or depression.
fossil fuels Energy source derived from organic matter stored in hydrocarbon deposits.
founder effect Genetic consequence of a few organisms that occupy a new habitat.
fracture hematoma (hē'-ma-TŌ-ma) A bruise that develops over the site of a fractured bone.
free radicals Highly reactive organic ions that have an unpaired electron, such as oxygen ions.
functional group Subunit on an organic molecule that helps determine how it reacts with other chemicals.
fundus The portion of any hollow organ that extends above the opening of that organ.
fungi Eukaryotic decay organism; kingdom that includes fungi. Singular is *fungus*.

gallbladder A small pouch, inferior to the liver, that stores bile and empties through the cystic duct.
gametes Sex cells (eggs and sperm) that join in fertilization.
ganglia (GANG-glē-a) A group of neuronal cell bodies lying outside the central nervous system.
gangrene Tissue death due to lack of blood flow.
gap junction Gap between nearby cells; used for communication.
gastric juice Fluid produced in the stomach.
gastric lipase Enzyme that digests short fatty acids, such as those found in milk.
gastric phase In digestion, hormonal and neural pathways that cause an increase in gastric wave force and secretion from gastric pits.
gastric Related to the stomach.
gated channels Membrane channels that open or close in response to a specific stimulus; are not open at all times.
gene flow Gain or loss of alleles in the gene pool of a population as individuals enter or leave by migration (as opposed to by birth and death).
general adaptation syndrome (GAS) The body's response to any stressor, in three stages: alarm, resistance, and exhaustion.
genetic diversity The genetic variation among individuals in a population or species.
genetic drift Random differences in the frequency of an allele within a small or isolated population due to chance events.
genome Total genetic content of an organism.
genotype The genes and alleles carried on the chromosomes.
genus A taxonomic subcategory of family.
germ cell A cell destined to become an egg or sperm.
gigantism A condition caused by hypersecretion of human growth hormone before closure of the epiphyseal plates.
glucagon (GLOO-ka-gon) A hormone produced by the alpha cells of the pancreatic islets (islets of Langerhans) that increases blood glucose level.
glucocorticoid (gloo'-kō-KOR-ti-koyd) Steroid hormones that maintain mineral balance, and control inflammation and stress.
glycocalyx Outside layer of a cell, composed of glycolipids and glycoproteins.
glycogen A large polysaccharide easily broken down to release individual glucose molecules.
glycolipid Lipid plus at least one carbohydrate group.
glycolysis The enzymatic breakdown of glucose into pyruvate, occurring within the cytoplasm.
glycoprotein Protein plus a carbohydrate.
goiter (GOY-ter) An enlarged thyroid.
Golgi (GOL-jē) **complex** Organelle involved with processing proteins and fatty acids.
gonad (GŌ-nad) A gland that produces gametes and hormones; ovary in female and testis in male.
gonadotropins Hormones that stimulate activity in the gonads (ovary and testes).
graded contraction A smooth transition from a small, weak contraction to a forceful contraction.
Graves disease The most common hyperthyroidism disease. It may be treated with surgical removal of part of the thyroid or the application of radioactive iodine to the thyroid.
gray matter Neuron cell bodies and dendrites within the CNS.
greenhouse effect Reflection of heat back to the Earth by carbon dioxide and other compounds; primary cause of global warming.
groin (GROYN) The depression between the thigh and the trunk.
growth factors Chemicals that stimulate cell growth.
gustation The sense of taste.
gyri (gyrus) Elevations separating individual sulci; the bumps on the brain.

habitat Where an organism lives.
haploid Having half the number of chromosomes of normal body cells, found in eggs and sperm.
haustra (HAWS-tra) Pouches created by strands of muscle in walls of large intestine that fill with undigested material.
haversian system Concentric rings of matrix laid by osteocytes, formed around a central canal; osteon.
hematocrit (hē-MAT-ō-krit) The percentage of blood made up of red blood cells.
hematopoiesis (hem'-a-tō-poy-E-sis) Process that forms blood cells.

hemispheric lateralization The isolation of a task to either the left or right hemisphere of the cerebrum.
hemoglobin (hē′-mō-GLŌ-bin) (Hb) A substance in red blood cells consisting of the protein globin and the iron containing red pigment heme that transports most of the oxygen and some carbon dioxide in blood.
hemolymph An oxygen-carrying fluid that circulates through the tissues of many invertebrates with open circulatory systems.
hemolytic disease of the newborn A blood disease caused by the destruction of the infant's red blood cells by antibodies produced by the mother; usually due to Rh blood type incompatibility.
hemothorax (hem′-ō-THŌ-raks) Blood in the pleural space.
hepatitis Viral inflammation of the liver caused by ingested toxins or other materials.
hepatocytes Liver cells (*hepato* = liver; *cyte* = cell).
herbivore (primary consumer) Organism that eats green plants.
heterotopic bone Bone that forms outside the usual areas for bone formation.
heterotrophs Organisms that cannot manufacture their own organic compounds and must obtain them from the environment.
heterozygous (het-er-ō-ZĪ-gus) Organism with one allele that codes for the dominant trait and the other that codes for a recessive trait (Aa).
hilum **S**ite of entry and exit for the nerves, blood vessels, and lymphatic vessels on most organs.
histamine A compound involved in allergic reactions that causes capillary leakage and increased fluid movement to affected tissues.
HIV (human immunodeficiency virus) The retrovirus that causes the disease AIDS.
homeostasis (hō′-mē-ō-STĀ-sis) Staying the same; the condition in which the body's internal environment remains relatively constant and within physiological limits.
homologous Similar in structure, function, or sequence of genetic information.
homozygous (HŌ-mō-zī-gus) Describes a gene in which both alleles are identical.
homozygous dominant Having both alleles code for the dominant trait (AA).
homozygous recessive Having both alleles code for the recessive trait (aa).
homunculus A proportional diagram of the structures of the human body as they are represented in the brain rather than having the proportions in which they physically exist.
hormone Compound secreted in one area of the body that is active in another area; usually carried by the blood.
host cell A cell that harbors a virus.
human chorionic gonadtrophin (kō-rē-ON-ik gō-nad-ō-TRŌ-pin) **(hCG)** A hormone that maintains pregnancy until the placenta is fully functional, by preventing degeneration of the corpus luteum.
human growth hormone (hGH) Hormone that stimulates the growth of muscle, cartilage, and bone and causes many cells to speed up protein synthesis, cell division, and burning fats for energy.
hydrogen bond Weak bond formed by electrical attraction between molecules.
hydrolases Digestive enzymes that catalyze the breakdown of large polymers by inserting water molecules between monomers.
hydrolytic enzymes Proteins that help decompose compounds by splitting bonds with water molecules.
hydrolyzed Undergoes process of splitting a water molecule, releasing H^+ and OH^-.
hydrophilic Having an affinity for water.
hydrophobic Lacking an affinity for water.
hyperpolarizing Altering the neuron transmembrane potential so that a stronger stimulus is needed to begin an action potential.
hypertension High blood pressure, defined as a diastolic number above 90.
hypertonic (hī′-per-TON-ik) Solution that causes cells to shrink due to loss of water by osmosis.
hypertrophy Enlargement of an organ due to enlarged cells rather than an increasing number of cells.
hypodermis The layer of connective tissue that holds the skin to the deeper organs composed of areolar connective tissue, adipose tissue, a large blood supply, and many connective tissue fibers.
hypothalamus (hī′-pō-THAL-a-mus) A portion of the diencephalon, lying beneath the thalamus and forming the floor and part of the wall of the third ventricle.
hypothyroidism Condition that occurs when the thyroid secretes too little T3 and T4.
hypotonic (hī-pō-TON-ik) Solution that causes cells to swell and perhaps rupture due to gain of water by osmosis.
hysterectomy (hiss-te-REK-tō-mē) The surgical removal of the uterus.

ileum (IL-ē-um) The longest region of the small intestine, measuring approximately 3 m.
immigration Movement to a location.
immune response The disease-fighting activity of an organism's immune system.
immunization The process of stimulating resistance to a specific disease through exposure to a nonpathogenic form of the disease-causing organism.
implantation Anchoring and settling of the embryo into the endometrial wall, starting placental formation.
in vitro (VE-trō) Literally, in glass; outside the body and in an artificial environment, such as a test tube.
incisors Teeth that function as cutting tools.
incomplete dominance Genetics that produces different phenotypes, based on the combination of alleles present in heterozygotes.
incontinence The inability to prevent urine leakage.
incus (IN-kus) The second of the auditory ossicles, joined to the malleus and the stapes.
indigenous Found only in a particular region.
inductive reasoning Type of reasoning that creates a general statement from observations.
inferior (in-FĒR-ē-or) Away from the head or toward the lower part of a structure; below; opposite of *superior.*
inflammation A localized method for increasing enzyme function, including swelling, redness, heat, and pain. The benefits include temporary tissue repair, blockage of continued pathogen entry, slowing of pathogen spreading, and quicker repair of the damaged tissue.
inguinal (IN-gwi-nal) **nodes** Lymph nodes located in the groin; pertaining to the groin.
inhalation The act of pulling air into the lungs.
inhibin Hormone that inhibits FSH production from the anterior pituitary, slowing sperm production.
inhibitory postsynaptic potentials (IP-SPs) A stimulus that moves the postsynaptic neuron membrane potential farther from threshold, making it more difficult to begin an action potential.
initiator An agent that causes cancerous changes in cellular functioning.
innate immunity Our inborn ability to defend against daily stresses and invasions of fungal, bacterial, or viral pathogens.
inner ear The portion of the ear that lies completely within the temporal bone, from oval window to round window. This area is filled with fluid and supports the membranous labyrinth.

insertion (of muscle) End of muscle that moves during contraction.
inspiratory reserve volume (IRV) Additional volume of air that can be added to the lungs after a normal inspiration; 1,900 ml in females, 3300 ml in males.
insulin (IN-suh-lin) A hormone produced by the beta cells of a pancreatic islet (islet of Langerhans) that decreases the blood glucose level.
integral protein A protein that spans the plasma membrane.
intelligent design The hypothesis that complex biological creatures were designed by intelligent beings rather than simply evolving through natural selection processes.
interferon A protein produced by virally infected cells that helps other cells respond to viral infection.
intermediate filament Protein in cytoskeleton that protects cell from mechanical stresses.
internal nares The twin openings at the back of the nasal passageway, leading to the upper throat.
internal respiration The exchange of gases between the blood in the systemic capillaries and the body's cells.
internal urethral sphincter Ring of involuntary smooth muscle that keeps the urethra closed.
interneurons (in'-ter-NOO-ronz) Neurons whose axons extend only for a short distance and lie completely within the brain, spinal cord, or a ganglion; they connect one neuron to another.
interosseus Between bones.
interstices The small fluid-filled spaces between tissue cells.
interstitial fluid Fluid that fills the spaces between cells of tissues.
intestinal phase The final phase of gastric digestion.
intramembranous Between membranes.
intrauterine device (IUD) Birth-control device made of plastic or copper that floats in the uterus and periodically hits the endometrial lining, preventing implantation.
intrinsic controls The heartbeat control maintained from within the heart that establishes the usual, day-in, day-out pace of heartbeats.
intrinsic factor Hormone produced by the parietal cells of the gastric pits that facilitates absorption of vitamin B12 .
intubation The insertion of a tube through the mouth or nose, through the larynx and into the trachea.
invertebrate Organism without a vertebral column, such as an earthworm, crab, or starfish.
ion A charged atom.
ionic bond Strong molecular bond, formed **between** atoms with opposite charges.
iris The colored portion of the vascular tunic of the eyeball visible through the cornea, which contains circular and radial smooth muscle.
ischemia Lack of oxygen to a tissue because of constriction or blockage of the blood vessels.
isotonic A solution with the same concentration as the cell cytoplasm.
isotope Chemically identical forms of an atom with different numbers of neutrons.

jejunum (je-JOO-num) The middle region of the small intestine, measuring approximately 2 m.

karyotype A micrograph of the chromosomes, arranged to show chromosome pairs.
keratin Tough, fibrous proteins that form hard structures, such as hair and nails.
keratinized Filled with keratin and therefore waxy.
kidney (KID-nē) One of the paired organs in the lumbar region that regulates the composition, volume, and pressure of blood and produces urine.
kinase A group of enzymes, all of which transfer a phosphate from one compound to another.
kingdom A high-level taxonomic classification.
Krebs (TCA) cycle The citric acid cycle, step two in the production of ATP from glucose, carried out in the mitochondrial cristae.

lacrimal glands Secretory cells, located at the lateral upper portion of each orbit, that secrete tears into ducts opening onto the surface of the eye.
lacrimal punctae Small holes in the corners of the eyelids that collect tears.
lactase Enzyme that digests carbohydrates.
lactiferous Producing milk.
lacuna (la-KOO-na) Hole in bone matrix that houses blood or nerve cell.
lanugo (la-NOO-gō) Soft hair covering the fetal skin.
laparoscopy Noninvasive surgery using fiber-optic cables, remote control, and tiny surgical tools.
laryngopharynx (la-rin'-gō-FAR-inks) The lowest level of the pharynx and the last part of the respiratory tract shared by the digestive and respiratory systems.
larynx Voice box (Adam's apple).
lateral / medial Opposite terms meaning found near the side or found near the middle.
lateral Found near the side; opposite of medial.
law of independent assortment Each trait is carried in the gametes as a separate entity, with no effect on any other trait.
law of segregation The separation of parental "heritable units" during gamete formation.
lethargy Tiredness and listlessness; inactivity because of fatigue or illness.
leukemia Cancer involving blood. A malignant disease of the blood-forming tissues characterized by either uncontrolled production of immature leukocytes (acute) or an accumulation of mature leukocytes that do not die at the end of their normal life span (chronic).
leukocytes White blood cells.
leutenizing hormone (LH) A hormone that stimulates the growth and functioning of the ovaries and testes.
Leydig (LĪ-dig) **cells** Cells in the testes that secrete testosterone.
ligament Dense regular connective tissue connecting bone to bone.
ligating Tying off a tube to close it.
light reaction Reaction in which chlorophyll absorbs a photon of light and releases an electron.
limbic system A part of the forebrain concerned with various aspects of emotion and behavior.
lingual Relating to speech or the tongue.
lipase An enzyme that chemically digests lipids.
lipid (LIP-id) Class of macronutrient made of long chains of carbon molecules, with many more carbon atoms and far fewer oxygen atoms than carbohydrates; fats.
lipoprotein lipase Enzyme that breaks chylomicrons down to short-chain fatty acids and glycerol.
liver Large organ under the diaphragm. It produces bile; detoxifies substances; stores glycogen, iron, and vitamins.
lobules Structures in the liver composed of a hepatic portal vein, a hepatic artery, and a bile duct.
lower esophageal sphincter Circular muscle located at the base of the esophagus.

lower respiratory tract Respiratory organs within the thoracic cavity, including the bronchial tree and the lungs.
lumen The inner, hollow portion of a tubular structure; the center of the blood vessel.
lungs Main organs of respiration that lie on either side of the heart in the thoracic cavity.
lymph (LIMF) **nodes** Small, encapsulated glands that are located to filter large volumes of lymph.
lymphatic system The tissues, vessels, and organs that produce, transport, and store cells that fight infection.
lymphocytes White blood cells that patrol the body, fight infection, and prevent disease.
lymphoma Cancer involving the lymphatic system.
lysosome (LĪ-sō-zīm) Chemical package produced by the Golgi complex, contains hydrolytic enzymes.

macerated Soaked until soft and separated into constituent parts.
macroevolution Evolution over long periods of time, resulting in vastly different organisms, typically referring to changes leading directly to new species.
macronutrients Carbohydrates, lipids, and proteins.
macrophage Large, phagocytic immune cell that patrols tissue, ingesting foreign material and stimulating immune cells.
macula (MAK-ū-la) A small, thickened region on the wall of the utricle and saccule that contains receptors for static equilibrium.
macula lutea The area of the retina immediately behind the pupil (*macula* = spot; *lutea* = yellow).
malignant Refers to a cancerous tumor that is harmful, invasive, and able to spread.
malleus (Mal-ē-us) The first of the auditory ossicles, attached to the tympanic membrane.
maltase Enzyme that digests carbohydrates.
mammary (MAM-ar-ē) gland Gland of the female that produces milk.
mass The amount of "substance" in an object ("weight" is the mass under a particular amount of gravity).
matrix The "ground substance" secreted by connective-tissue cells; determines the characteristics of the connective tissue.
mechanical digestion The physical crushing, chopping, and cutting of food.
mechanically regulated Describes membrane channels that open or close in response to physical deformation of the channel.
mechanoreceptor (me-KAN-ō-rē-sep-tor) Sensory receptor that detects mechanical deformation of the receptor or adjacent cells; detecting touch, pressure, vibration, proprioception, hearing, equilibrium, and blood pressure.
medial Found near the middle; opposite of *lateral*.
mediastinum The central portion of the thoracic cavity between the lungs, containing the heart, major blood vessels, and lymphatics.
medulla (me-DOO-la) Inner portion of the organ.
medulla oblongata Portion of the brain stem immediately adjacent to the spinal cord, associated with heart rate, breathing controls, and blood pressure.
megakaryocytes Large cells in the bone marrow that produce platelets.
Meissner corpuscles (MĪS-ner KOR-pusućlz) Structures in the dermis that register light touch.
melanin A dark brown, UV-light-absorbing pigment produced by specific cells.
melanocytes Cells that produce melanin, a brown, light-absorbing pigment.
membrane potential The difference in electrical charge between two sides of a membrane.
membrane Structure that delineates a component, such as a cell or organ.
meninges Three protective membranes covering the brain and spinal cord.
meningitis Inflammation of the meninges.
menisci Fat pads within joints that cushion bones and assist in "fit."
menstruation (men'-stroo-Ā-shun) Periodic discharge of blood, tissue fluid, mucus, and epithelial cells; the menstrual cycle or menses.
mesenteric Pertaining to the membranous fold in the abdominal cavity attaching many of the abdominal organs to the body.
mesenteries Folds in the lining of the abdominal cavity that help to secure the digestive organs.
mesoderm Middle layer of embryonic cells.
messenger RNA (mRNA) RNA that takes information from DNA into the cytoplasm.
metabolism The chemical reactions that take place in the body.
metabolize To perform a process in an organism, including both breakdown and buildup of organic compounds.
metastasis The spread of cancer cells from their primary site to other sites.
microevolution Evolution occurring through a series of small genetic changes, typically referring to changes within populations.
microfilament Protein in cytoskeleton, responsible for basic shape, cellular locomotion, muscle contractions, and movement during cell division.
micronutrients Vitamins and minerals.
microphage (MIK-rō-fāj) A small phagocyte mainly found in the nervous system.
microtubule Long strings of coiled tubulin that serve as tracks for organelle movement.
microvilli Small hair-like folds of the cell membrane that increase the cell's surface area for absorption.
middle ear The portion of the ear from the tympanic membrane to the oval window, encased within the temporal bone and filled with air.
migrating motility complexes Part of the peristaltic wave that moves the chyme along the small intestine.
milled Ground, as in grain that has been ground into flour.
mineralocorticoids Steroid hormones involved in maintaining water and ion balance.
minimal media Growth media consisting only of the essential requirements for survival.
mitochondrion (mī-tō-KON-drē-on) Organelle that processes energy. Plural is *mitochondria*.
mitosis (mī-TŌ-sis) Division of a cell into two daughter cells.
mitral Pertaining to the left ventricle of the heart.
molars and **premolars** Teeth that function as grinding instruments.
molecule Group of similar or dissimilar atoms bound together.
monoculture The practice of planting a single species over large tracts of land.
monocyte (MON-ō-sit') The largest type of white blood cell, characterized by a granular cytoplasm.
morphogenesis Formation of organs and tissues during development.
morula (MOR-ū-la) A solid mass of cells that can develop into any type of cell.
motor neurons Neurons that conduct impulses from the brain.
motor unit The group of muscle cells controlled by one motor neuron.
mucosa (mū-KŌ-sa) A membrane that lines a body cavity that opens to the exterior, also called mucous membrane.

mucosa-associated lymphoid tissue (MALT) Lymphoid tissue in the tonsils, small intestine, and other regions in contact with the exterior.
multifactorial disorder Genetic disorder due to a combination of genetic and environmental factors.
multifactorial trait Polygenic trait that is also influenced by environment.
mumps A common infection of the salivary glands; causes swelling of the glands, sore throat, tiredness, and fever.
muscle tone Constant partial contraction of muscle when the body is "in shape."
muscular tissue Dense tissue that provides movement and heat.
muscularis mucosae (MUS-kū-la'-ris mū-KŌI-sē) A thin layer of smooth muscle fibers underlying the mucosa of the GI tract that gives the tract the ability to move substances lengthwise.
myelin White lipids and phospholipids wrapped around neural processes that aid in faster transmission.
myeloid Pertaining to bone marrow.
myocardial infarction (mī'-ō-KAR-dē-al in-FARK-shun) **(MI)** Large-scale death of heart tissue due to interrupted blood supply (heart attack).
myofiber Muscle cell.
myofibrils Linearly arranged groups of the contractile proteins actin and myosin.
myoglobin (mī-ō-GLŌB-in) Oxygen-carrying protein in muscle cells.
myometrium (mī'-ō-MĒI-trē-um) The smooth muscle layer of the uterus.
myosin (MĪ-ō-sin) Protein that functions in muscle contraction; see *actin*.
MyPyramid Personalized dietary guidelines from the U.S. Department of Agriculture (www.mypyramid.gov).
myxedema (mik-sē-DĒI-ma) Condition in which thyroid works normally at birth but fails to secrete enough hormone in adult life, causing slow heart rate, low body temperature, dry hair and skin, muscular weakness, general tiredness, and a tendency to gain weight.

nasopharynx (nā'-zō-FAR-inks) Upper throat, including the nasal openings and the soft palate.
natural selection A natural process that favors individuals better adapted to the environment, ensuring that those traits are passed to the next generation.
negative feedback System that tends to return to homeostasis.
neonate The newborn child, from immediately after birth to approximately one month of age.
nephron The filtering unit of the kidney.
nerve deafness Condition in which sound is either not detected or the nerve impulse is not transmitted to the brain.
nerves A bundle of axons and/or dendrites covered with connective tissue found outside the central nervous system.
nervous tissue Tissue that responds to the environment by detecting, processing, and coordinating information.
neuroendocrine Describes cells that can both carry nerve impulses and produce hormones.
neuroglia (noo-RŌG-lē-ə) Cells that support and protect within the nervous system, including cells that provide nutrients, remove debris, and speed impulse transmission.
neuromuscular junction Junction between a nerve cell and the motor unit it controls.
neuron (NOO-ron) A nerve cell that sends and receives electrical signals.
neurotransmitter A chemical used to transmit a nervous impulse from one cell to the next.
neutron The neutral particle in the atomic nucleus.
neutrophil (NOO-trō-fil) A type of white blood cell characterized by granules that stain pale lilac with a combination of acidic and basic dyes.
niche A specific part of a habitat that can be occupied by one type of organism.
nitrification The formation of nitrates in the atmosphere.
nitrogenous wastes Compounds containing nitrogen, such as urea, that are produced during protein metabolism.
nociceptors Nonadapting pain receptors in the skin (*noci* = pain).
nonpolar Molecule that is electrically balanced.
norepinephrine (nor'-ep-el-NEF-rin) **(NE)** A hormone secreted by the adrenal medulla that produces actions similar to those that result from sympathetic stimulation. Also called **noradrenaline** (nor-a-DREN-a-lin).
nuclear envelope Membrane surrounding a nucleus.
nuclear pore Opening in nuclear envelope that allows material to enter and exit a nucleus.
nuclei Areas of concentrated neuronal cell bodies in the brain.
nucleoli Dark regions of chromatin that produce ribosomal RNA and assemble ribosomes. Singular is nucleolus.
nucleoplasm Fluid within the nucleus, containing the DNA.
nucleus (NOO-klē-us) Compartment of a cell that contains genetic information.
nucleus pulposus A soft, elastic substance in the center of intervertebral discs.
nutrients Ingredients in food that are required by the body.

obesity (o-BĒ-si-tē) Body weight more than 20% above a desirable standard due to excessive fat.
obligate anaerobes Bacteria that require an oxygen-free environment.
obstetrics The medical field devoted to prenatal and maternal care.
obstructive In the respiratory system, blocking the normal flow of gases through the lungs.
olfaction The sense of smell.
olfactory bulb A mass of gray matter containing neurons that form synapses with neurons of the olfactory (I) nerve, lying below the frontal lobe of the cerebrum on either side of the ethmoid bone.
oligodendrocyte (OL-i-gō-den'-drō-sīt) A neuroglial cell that supports neurons and produces a myelin sheath around axons of neurons of the central nervous system.
omega-3 fatty acid Alpha-linoleic acid; a fat with an omega functional group on the third carbon. Found in vegetable and fish oils.
omnivore Animal that can eat either plants or animals.
oncogenes Genes that cause cancer.
oncologist A physician who specializes in the treatment of cancer.
oocyte Egg; the female gamete.
oogenesis (ō '-ō-JEN-e-sis) Formation and development of female gametes (oocytes).
open system A system with a starting point and an ending point rather than a continuous circular flow.
opportunistic infection An infection caused by a common and usually nonthreatening microorganism that is able to cause disease due to a compromised immune system.
opposable thumb A thumb that can move across the other four digits.
optic chiasma The physical crossing of the left and right optic nerves.
oral contraceptive A combination of estrogens and progestins that alters the natural hormonal rhythms of the female to prevent ovulation.
orbital Region where electrons are found around an atomic nucleus.

order A taxonomic subcategory of class.
organ A structure composed of more than one tissue having one or more specific functions.
organ of Corti The organ responsible for transmitting sound waves to the brain via nerve impulses.
organ system A group of organs that perform a broad biological function, such as respiration or reproduction.
organelle Typically, a membrane-bound structure suspended in the cytosol; hair-like projections from the cell may also be called organelles.
organism living individual.
orgasm A series of wave-like muscular contractions, and an intense pleasurable sensation, during sex.
origin (of muscle) End of muscle that remains stationary during contraction.
oropharynx (or'-ō-FAR-inks) The area directly behind the tongue, is covered by the uvula when it hangs down.
osmolarity Osmotic pressure of a solution.
osmosis (oz-MŌ-sis) Movement of water across a membrane, driven by differences in concentration on each side of the membrane.
ossify To form hard bone.
osteoblasts (OS-tē-ō-blasts') Immature bone cells not yet surrounded by bony matrix.
osteoclast (OS-tē-ō-clast') Cell that breaks down bone by removing calcium.
osteocytes Mature bone cells surrounded by bony matrix.
osteoid Stage of bone matrix before it calcifies.
osteon (OS-tē-on) The basic unit of structure in adult compact bone, consisting of a central (haversian) canal with its concentrically arranged lamellae, lacunae, osteocytes, and canaliculi. Also called a haversian (ha-VER-shan) system.
otitis media Inflammation of the middle ear that fills it with fluid, distending the eardrum.
outer ear The portion of the ear that extends from the fleshy pinna (external ear cartilage) through the auditory canal of the ear to the eardrum (tympanic membrane).
oval window The fibrous connective tissue covering on the opening into the inner ear; the stapes attaches to the oval window.
ovarian (ō-VAR-ē-an) **cycle** A monthly series of events in the ovary associated with the maturation of a secondary oocyte.
ovary (Ō-var-ē) Female gonad, produces oocytes and the estrogens, progesterone, inhibin, and relaxin hormones.
ovulation (ov-ū-LĀI-shun) The rupture of a mature ovarian (Graafian) follicle with discharge of a secondary oocyte into the pelvic cavity.
oxygen debt The amount of oxygen needed to convert the lactic acid produced by anaerobic respiration into pyruvic acid and burn it entirely to CO_2, H_2O, and energy.
oxyhemoglobin Hemoglobin molecule with at least one oxygen molecule bound to the iron center.
oxytocin (ok'-sē-TŌI-sin) Hormone that initiates labor and causes the cells of the mammary gland to contract during the "milk let-down" response.

P wave The deflection wave of an electrocardiogram that signifies atrial depolarization.
Pacinian (pa-SIN-ē-an) **corpuscles** Structures deep in the dermis, near the hypodermis, that register pressure.
palindrome A group of nucleotides with the same sequence when read in either direction (for example, CGTTGC).
pancreas (PAN-krē-as) A soft, oblong organ lying along the greater curvature of the stomach.
pancreatic (pan'-krē-AT-ik) **amylase** Enzyme that digests carbohydrates.
pancreatic juice The fluid produced by the pancreas and released into the small intestine.
pancreatic lipase The enzyme that removes two of the three fatty acids from ingested triglycerides.
pandemic An epidemic in a wide geographic region.
papilla Any small, rounded projection extending above a surface.
papillary muscles Tufts of muscle extending from the walls of the ventricles, anchoring the valves.
paracrine Hormone that affects only local cell.
paradigm A model or pattern; a way of seeing a situation based on cultural assumptions, concepts, and values.
parasympathetic (par'-a-sim-pa-THET-ik) **division** One of the two subdivisions of the autonomic nervous system, originating in the brain stem and the sacral portion of the spinal cord; primarily concerned with activities that conserve and restore body energy.
parathyroid (par-a-THĪ-royd) **gland** One of usually four small endocrine glands embedded in the posterior surfaces of the lateral lobes of the thyroid gland.
parathyroid hormone (PTH) A hormone secreted by the chief cells of the parathyroid glands that increases blood calcium level and decreases blood phosphate level.
parietal Of or relating to walls of a cavity, as in the walls of the cranial cavity; also, a parietal part.
parotid glands Salivary glands located below and in front of the ears.
partial pressure The percentage of total gas pressure exerted by a single gas in the mixture.
partition Dividing available resources into discrete parts to reduce competition.
pathogen Agent that produces disease.
pectoral girdle The bones that attach the arm to the axial skeleton; the shoulder bones.
pedigree chart Representation of genetic transmission of traits through families.
pelvic cavity Cavity that contains the urinary bladder, internal organs of reproduction, and part of the large intestine.
pelvic girdle The bones that connect the leg to the axial skeleton; the hip bones.
penis (PĒ-nis) The organ of urination and copulation in males; used to deposit semen into the female vagina.
pepsin Enzyme that digests proteins.
pepsinogen An inactive precursor of the enzyme pepsin.
peptide bond Covalent bond between the carboxyl group of one amino acid and the amino group of the adjacent amino acid.
percolation Filtration through a porous substance.
perforins Molecules released by a T cell that break through the plasma membrane of the infected cell.
pericardium (per-i-KAR-dē-um) Membrane surrounding the heart.
perimetrium (per'-i-MĒ-trē-um) The outer covering of the uterus.
perimysium (per-i-MĪZ-ē-um) An inner connective tissue covering and supporting a group of muscle cells.
periodic table Table that organizes all atoms by structure.
periosteum (per'-ē-OS-tē-um) Membrane that covers bone.
peripheral nervous system (PNS) That portion of the nervous system that consists of the nerves and sensory organs.
peripheral protein A protein that sits on the inside or the outside of the cell membrane.
peristaltic wave Rhythmic muscular contractions of a tube that force contents toward the open end.
peritoneum Membrane lining the abdominal cavity.

peritubular capillaries Capillaries that surround the nephron (*peri* = around; *tubular* = nephron tubules).
Peyer's (PĪ-erz) **patches** Clusters of lymph nodules that are most numerous in the ileum.
phagocytes (FAG-ō-sītz) Cells that endocytose (engulf) pathogens.
phagocytosis (fag'-ō-sī-TŌ-sis) Cell eating, or taking in large molecules and particles through vacuoles.
pharynx Throat.
phenotype An organism's observable characteristics as a result of the genes and alleles being expressed.
phospholipid Compounds containing phosphoric acid and a fatty acid.
photopigment An organic compound that changes in response to light.
photoreceptor Receptor that detects light in the retina.
photosynthesis Process of producing carbohydrates with sunlight, chlorophyll, carbon dioxide, and water.
phylum A taxonomic subcategory of kingdoms. Plural is *phyla*.
phytoplankton Microscopic and macroscopic plants that float in the upper, lighted reaches of the water column.
pia mater (PĪ-a MĀ-ter *or* PĒ-a MA-ter) The innermost of the three meninges (coverings) of the brain and spinal cord.
pinna (PIN-na) The projecting part of the external ear composed of elastic cartilage and covered by skin and shaped like a trumpet.
pinocytosis (pin-ō-sī-TŌ-sis) Process by which a cell drinks or takes in a small quantity of the extracellular fluid.
pioneer species The first plant species to colonize a newly established area.
pituitary (pi-TOO-i-tār-ē) **dwarfism** A condition caused by hyposecretion of human growth hormone during development.
placenta (pla-SEN-ta) Structure that connects uterus to fetus, providing nourishment.
placenta previa Condition in which the placenta grows near or over the cervical opening of the uterus, blocking the passage of the fetus during birth.
plantae The kingdom that includes plants.
plaque (PLAK) A combination of bacterial colonies, their wastes, leftover sugars from chewed up food, epithelial cells from the host, and saliva.
plaques (PLAKS) Fatty deposits of cholesterol that form in the arteries.
plasma (PLAZ-ma) The clear, yellowish fluid portion of blood. The extracellular fluid in blood vessels; blood minus the formed elements.
plasmids Circular pieces of double-stranded DNA outside the nucleus or the main DNA of the cell.
platelet plug The first step in formation of a clot; a fragile plug that slows blood flow in small wounds.
pleura (PLOO-ra) The serous membrane that covers the lungs and lines the walls of the chest and the diaphragm. The visceral pleura lines the lungs themselves, while the parietal pleura adheres to the walls of the cavity.
pleural cavity Small potential space between the visceral and parietal pleurae filled with serous fluid.
pleurisy (PLOO-ra-sē) Inflammation of the covering surrounding the lungs (the pleura), causing painful breathing.
pluripotent cells Cells with the potential to become any adult cell type.
pneumonia (noo-MŌI-n ē-a) Buildup of fluid in the lung, often in response to bacterial or viral infection.
pneumonic Of or pertaining to the lungs.
pneumotaxic (noo-mō-TAK-sik) A part of the respiratory center in the pons that sends inhibitory impulses to the inspiratory area, preventing overinflation of the lungs.
pneumothorax (noo'-mō-THŌI-raks) Air in the pleural space.
polar covalent bond Covalent bond that is electrically unbalanced—for example, water.
polygenic Trait coded on several genes.
polymer Long chain of repeating subunits.
polymerase chain reaction (PCR) A series of reactions that amplifies DNA using the same enzymes that cells use to synthesize DNA.
polymerase The enzyme that adds nucleotides during DNA duplication.
polymerization The chemical bonding of monomers to form a larger molecule.
polyp Growth protruding from a mucous membrane.
polyspermy Many sperm entering one ovum.
pons The area superior to the medulla oblongata, involved in transfer of information and respiratory reflexes.
population All representatives of a specific organism found in a defined area.
portal systems Vascular systems that carry blood from arteries to veins to capillaries to veins, back to capillaries, then on to veins and the heart.
postnatal After birth.
postsynaptic (pōst-sin-AP-tik) **neuron** The neuron that begins after passing the synapse; its dendrites pick up diffusing neurotransmitters.
precapillary sphincter (SFINGK-ter) A ring of smooth muscle cells at the origin of the capillaries to regulate blood flow into them.
premature baby Infant born prior to the normal gestational period of 40 weeks.
premenstrual dysphoric disorder (PMDD) Group of physiological and emotional symptoms linked to the menstrual cycle.
presynaptic neuron The neuron that lies before the synapse, whose axon leads to the synapse.
primary cancer The original site of tumor development; can metastasize to form secondary cancers.
primary motor area A region of the cerebral cortex in the frontal lobe that controls specific muscles or groups of muscles.
primary succession Colonization of life on bare rock or sand.
prime mover The muscle in an antagonistic pair that shortens during a specific movement; agonist.
producers Organisms that create their own organic compound nutrients from inorganic substances and light; mainly green plants.
progesterone (prō-JES-te-rōn) A female sex hormone produced by the ovaries; helps prepare the uterus for implantation and mammary glands for milk secretion.
prokaryotic Type of cell with no internal membrane-bound compartments, usually having only genetic material as organelles.
prolactin (PRL) Hormone that stimulates milk production in females.
prolapse (PRŌ-laps) Movement (dropping, sliding, or falling) of an organ from its original position in the body, usually because of gravity or pressure.
promoters Environmental agents that increase the likelihood that an initiator will affect cellular functioning.
proprioception The reception of stimuli from within the body that give information on body position and posture.
prostaglandin (pros'-ta-GLAN-din) A membrane-associated lipid; released in small quantities and acts as a local hormone.

protein A macronutrient consisting of carbon, hydrogen, oxygen, nitrogen, and sometimes sulfur and phosphorus; synthesized on ribosomes and made up of amino acids linked by peptide bonds.
prothrombin (prō-THROM-bin) Blood-clotting factor synthesized by the liver, released to the blood, and converted to active thrombin during blood clotting.
proton The positive particle in the atomic nucleus.
proximal / distal Opposite terms meaning near the core of the body versus farther from the core.
puberty (PŪ-ber-tē) The time of life when the secondary sex characteristics begin to appear and sexual reproduction becomes possible; usually between ages 10 and 17.
pulmonary (PUL-mo-ner'-ē) **trunk** The vessels leaving the right side of the heart, going toward the lungs.
pulmonary and **aortic** (ā-OR-tik) **valves** Valves between the ventricles of the heart and the great vessels. The pulmonary valve lies between the right ventricle and the pulmonary arch; the aortic valve lies between the left ventricle and the aorta.
pulmonary circuit Blood flow from the heart to the lungs and back to the heart.
pulmonary edema Fluid buildup in the lungs due to congestive heart failure.
pulp Soft tissue near the tooth's nerve.
pupil The hole in the center of the iris.
Purkinje fibers Conduction myofibers that reach individual cells of the ventricles.
pyloric (pī-LOR-ik) **sphincter** Located at the end of the stomach, it opens to allow chyme to enter the small intestine when it is chemically ready.
pyrogens (PĪ-ro-jenz) Proteins that reset the body's thermostat to a higher temperature.
pyruvate Three-carbon compounds that form in the cytoplasm from the initial breakdown of glucose.

QRS complex The deflection waves of an electrocardiogram that represent the beginning of ventricular depolarization.
Q-T interval The total time of ventricular contraction and relaxation.
quadrant Four-part division of the body used to describe organ location.
quiescent Resting, quiet, inactive.

radiation The transfer of heat from a warm body to the surrounding atmosphere.
radioactive decay Spontaneous disintegration of a radioactive substance into another element through nuclear division and the release of energy.
radioisotope Isotope that decays spontaneously, releasing energy.
recessive An allele of a gene that determines phenotype only when two like alleles are present.
recombinant DNA The product of splicing genes.
rectus abdominus "Six-pack" muscles that stabilize the trunk.
referred pain Pain the brain interprets as coming from an area other than its actual origin.
reflex Fast response to a change (stimulus) in the internal or external environment.
relative refractory period The period immediately after an action potential when the sodium channels are in their original position, but the transmembrane potential has not yet stabilized at resting levels.
relaxin A female hormone produced by the ovaries and placenta that relaxes the smooth muscle and helps dilate the cervix to ease delivery.
remission A decrease of disease symptoms leading to an apparent curing of the disease; indicates that the disease is still present but dormant.
renal (RĒ-nal) **pyramids** Cone-shaped structures formed from an accumulation of collecting ducts in the medulla of the kidney.
renal pelvis A cavity in the center of the kidney that collects urine and passes it to the ureters.
reservoir Location that holds a compound in a way that is inaccessible to the user.
residual volume (RV) The amount of air that always remains in the lungs.
respiratory membrane The thin, membranous "end" of the respiratory system where gases are exchanged.
respiratory system The system that brings oxygen to the blood and removes carbon dioxide from it.
respiratory zone Portion of the respiratory tract where gas exchange occurs.
reticular (re-TIK-ū-lar) **activating system (RAS)** A portion of the reticular formation that has many ascending connections with the cerebral cortex; produces generalized alertness or arousal from sleep when active.
reticular formation A network of small groups of neuronal cell bodies beginning in the medulla oblongata and extending superiorly through the central part of the brain stem.
retina (RET-i-na) The deep coat of the posterior portion of the eyeball consisting of nervous tissue that detects light and creates nerve impulses.
retroverted (tipped) uterus Condition in which the uterus lies against the rectum.
retrovirus A virus carrying RNA as its genetic material, along with an enzyme to copy the viral RNA into the host cell's DNA.
reverse transcriptase An enzyme that forms DNA from RNA.
rhinoplasty Surgery on the nose done to treat a "deviated septum" or for cosmetic reasons.
rhodopsin Visual pigment that responds to low levels of white light.
ribosome (RĪ-bō-sōm) Organelle that synthesizes proteins.
ribs Flattened bones that emerge from the cervical or thoracic spine to shape the thorax.
rigor mortis Rigidity that occurs in muscles after death.
RNA or **DNA primer** A short segment of RNA or DNA binding to the original DNA strand, initiating DNA replication.
root nodules Swellings on the root hairs of legumes and other plants containing nitrogen-fixing bacteria.
rough endoplasmic reticulum (RER) Membrane that processes and sorts proteins synthesized by ribosomes.
rugae (ROO-gē) Folds in the wall of the stomach that permit expansion.

saccule Small circular vesicle used to transport substances within a cell.
salivary glands Glands in the oral cavity that secrete saliva to moisten the oral mucosa.
sarcolemma (sar'-kō-LEM-ma) The cell membrane of a muscle fiber (cell), especially of a skeletal muscle fiber.
sarcoma Cancer of soft tissue, such as connective tissue.
sarcomere (SAR-kō-mēr) The contractile unit of a myofiber.
Schwann (SCHWON) **cell** A neuroglial cell of the peripheral nervous system that forms the myelin sheath wrapping around the axon in jelly-roll fashion.
scientific method System of study that includes observation, hypothesis generation, testing, data collection, drawing conclusions, and communication of the results of the experiment.

sclera (SKLE-ra) The white coat of fibrous tissue that forms the superficial protective covering over the eyeball.
scrubbers Equipment in a smokestack that removes impurities from the escaping gas.
sebaceous (se-BĀ-shus) **glands** Oil glands found in the dermis of the skin, associated with hair follicles.
secondary succession Ecological change in an ecosystem after a disturbance.
secrete To move (usually actively transport) substances from cells, blood, or lymph for functional use or excretion as urine. Noun form is *secretion*. Secretion can be either a process or a chemical substance.
secreted In this sense, actively transported from the blood to the filtrate.
secretin Hormone that decreases gastric secretions.
secretion In this sense, moving substances from the blood to the forming urine in the kidneys.
secretory phase Phase of the menstrual cycle when the endometrial glands function.
selection pressure Any external forces that cause differences in the fitness of individuals having particular alleles.
self-pollinating Transferring the pollen of a flower directly to the stigma of the same flower.
semen The fluid containing sperm and other components, formed as the sperm moves through the reproductive system.
seminal vesicles Glands on the posterior base of the urinary bladder that secrete an alkaline, fructose-rich fluid.
semipermeable Describes a membrane that is permeable to some compounds but not others.
senescent At the stage of aging or growing old.
sensory neurons Neurons that carry sensory information.
septal cells Cells found in the alveolar membrane that secrete surfactant.
septicemic Describes the invasion of a pathogen in the bloodstream; blood poisoning.
septum (SEP-tum) A wall dividing two cavities.
sex-influenced trait Trait carried on autosomal chromosomes that is more common in one sex than another.
sex-linked trait Trait coded by genes that are carried on the one sex chromosome with no counterpart on the other sex chromosome.
sexual dimorphism Morphological differences between the two genders.
simple epithelium Single layer of cells that often functions as a diffusion or absorption membrane.
sinoatrial (si-nō-Ā-trē-al) **(SA) node** A small mass of heart cells located in the right atrium that spontaneously depolarize and generate the resting heartbeat. Also called the pacemaker.
skeletal muscle Contractile tissue composed of protein filaments arranged to move the skeletal system.
sleep apnea The periodic cessation of breathing during sleep (*a* = without; *pnea* = breath).
sliding filament model Standard explanation of how a muscle cell creates contraction.
slow block Deactivation of the sperm receptors in the zona pellucida, preventing interaction between a fertilized egg and a second sperm.
slow-twitch fiber Myofibril that contracts relatively slowly.
smog Nitrogen oxides and hydrocarbon pollution that turns brown or gray in sunlight.
smooth endoplasmic reticulum (SER) Membrane that synthesizes fatty acids and steroid hormones.
socioeconomic level The relative position of an individual within the larger population in terms of social and economic factors.
sodium potassium exchange pump (Na^+/K^+ ATPase) An active transport pump located in the plasma membrane that transports sodium ions out of the cell and potassium ions into the cell at the expense of cellular ATP.
soft connective tissue Connective tissue with a matrix composed of a semifluid ground substance, fibroblasts, and white blood cells.
solute Salts, ions, and compounds dissolved in a solvent, forming a solution; water is the most common solvent in the human body.
somatic (sō-MAT-ik) Related to the body, in contrast to the gametes.
somatic division Division of the nervous system involved in conscious movement.
somatostatin A water-soluble hormone that prevents the secretion of growth hormone; literally to "keep the body the same" (*soma* = body).
special senses The five senses of the body: hearing, vision, taste, smell, and balance.
species A precise taxonomic classification, consisting of organisms that can breed and produce offspring capable of breeding.
species diversity The variation in species in a particular location.
specific gravity A ratio of the density of a substance to the density of pure water.
specific immunity Immunity directed by white blood cells, antibodies, and macrophages that specifically target individual pathogens.
spermatic cord The artery, vein, nerve, lymphatics, and vas deferens that lead from the abdominal cavity to the testes.
spermatogenesis The formation of sperm cells.
spermicide Birth-control measure that kills sperm inside the female reproductive tract.
spider veins Small, visible yet flat veins on the surface of the body, made visible by trapped red blood cells.
spinal (SPĪ-nal) **cord** The part of the central nervous system contained within the vertebral canal (spinal cavity).
spinal cavity Cavity inside the vertebral column; houses the spinal cord.
spinal nerves One of the 31 pairs of nerves that originate on the spinal cord from posterior and anterior roots.
spliced Joined together; two pieces of DNA artificially joined together to form new genetic combinations.
squamous (SKWĀ-mus) **cell** Flattened cell; squamous epithelium forms a diffusion membrane.
stable angina Pain that develops in the heart only under specific and identifiable conditions, such as strenuous exercise or smoking.
stapes The third of the auditory ossicles, that transfers the movement of the tympanic membrane directly to the oval window and the fluid of the inner ear.
Starling's law When the ventricles are stretched by increased blood volume, they recoil with matching force. This increased blood flow to the heart, which occurs when we start hard physical work, causes the heart to respond with more forceful pumping.
statistical significance An experimental result that would occur by chance in less than 1 experiment in 20; the accepted level in modern science.
stem cells Undifferentiated cells that remain able to divide and specialize into functional cells.
stent Medical instrument that is inserted into a weakened blood vessel for support.
stereocilia (ste'-rē-ō-SIL-ē-a) Groups of extremely long, slender, nonmotile microvilli.
stereoscopic vision Three-dimensional vision created by two slightly different views superimposed on one another.
stereoscopic Depth perception gained through use of the visual field of both eyes.

stomach A J-shaped organ that lies beneath the esophagus and is divided from the esophagus and the small intestine by two sphincter muscles.
stratified epithelium Several layers of epithelial cells.
stratosphere The portion of the atmosphere from about 15 to 50 km above the Earth; contains the ozone layer.
stratum corneum The top layer of the epidermis that is composed of dead cells joined by strong cell-to-cell junctions.
stratum functionalis Outer layer of endometrium that grows and sheds in response to hormone levels in the blood.
striations A series of parallel lines.
submandibular glands Salivary glands located under the tongue that produce thick, ropy saliva with a large concentration of mucus.
submucosa Second layer of the GI tract, found under the mucosa, and including the glands, nerves, and blood supply for the GI tract.
succession The sequential change in species in an ecosystem.
sucrase Enzyme that digests carbohydrates.
sulci (sulcus) Shallow grooves on the surface of the brain.
summation Buildup of contractions inside a myofiber.
superior / inferior Opposite terms meaning above and below.
supplemental media Growth media with added nutrients and growth factors.
surfactant Detergent-like compound that prevents alveolar membranes from sticking together.
sustainability The wise exploitation of resources and energy to ensure resources for future generations.
suture (SOO-chur) Inflexible joint between two fixed bones.
symbiotic Intimate coexistence of two organisms in a mutually beneficial relationship.
sympathetic (sim'-pa-THET-ik) **division** One of two subdivisions of the autonomic nervous system, originating in the thoracic segment and the first two or three lumbar segments of the spinal cord; primarily concerned with processes involving the expenditure of energy.
sympathetic chain A cluster of cell bodies of sympathetic neurons close to the body of a vertebra. These are found in the neck, thorax, and abdomen on both sides of the vertebral column and are connected in a chain on each side of the vertebral column.
synapse (SIN-aps) Gap between neurons, across which a nerve impulse must flow via chemical signal.
synarthrotic Describes a joint that is not movable.
synergistic (syn-er-JIS-tik) **pair** Muscles with opposite actions working together to provide smooth and controlled movements; *antagonistic pair*.
syngamy (SIN-ga-mē) Process in which one sperm penetrates the zona pellucida and fuses with the oocyte membrane.
synovial fluid Fluid secreted by the inner membrane of a synovial joint, similar in viscosity to egg white.
synovial joint A fully movable or diarthrotic joint in which a synovial (joint) cavity is present between the two articulating bones.
systemic circuit Blood flow from the heart to the tissues of the body and back to the heart.
systole Contraction of the heart.

T tubules Tubes formed in the sarcolemma that cross through the muscle cell, carrying contractile impulses to all parts of the muscle cell.
T wave The deflection of an electrocardiogram that represents ventricular repolarization.
tachycardia Resting heart rate above 100 beats per minute.
target cell A cell whose activity is affected by a particular hormone.
taxonomy The study of classification, based on structural similarities and common ancestry.
TCA (Krebs) cycle The citric acid cycle, step two in the production of ATP from glucose, carried out in the mitochondrial cristae.
tectoral membrane The structure within the organ of Corti that deforms with sound waves and generates nerve impulses.
telomeres Stretches of repeating DNA bases located at the tips of chromosomes.
tendon Dense regular connective tissue connecting muscle and bone.
terminal bulb The swollen terminal end of the axon that releases neurotransmitters into the synapse.
testosterone (tes-TOS-te-rōn) A male sex hormone needed for development of sperm, male reproductive organs, secondary sex characteristics, and the body.
tetanus State of continuous contraction in a myofibril.
thalamus (THAL-a-mus) A large, oval structure located on either side of the third ventricle of the brain; main relay center for sensory impulses heading to the cerebral cortex.
theory A general uniting principle of science, upheld by observation and many experiments.
therapeutic abortion Removal of the developing embryo for medical reasons.
thoracic (thor-AS-ik) **cavity** The chest and its contents.
threshold stimulus The minimal amount of stimulation needed to cause a response.
thymus (THĪ-mus) **gland** A bilobed organ located in the upper thoracic cavity behind the sternum and between the lungs in which T cells mature.
thyroid (THĪ-royd) **stimulating hormone (TSH)** Hormone that activates the thyroid to produce T3 (triiodothyronine) and T4 (thyroxin), which maintain basal metabolic rate.
thyroid (THĪ-royd) **cartilage** Shield-shaped cartilage that composes the front of the larynx.
tidal volume (TV) The volume of air inhaled per minute during normal breathing, approximately 500 ml.
tissue Group of cells with similar function.
titer Level of a compound or antibody in the blood.
tonsils (TON-silz) A group of large lymphatic nodules embedded in the mucous membrane of the throat.
trabeculae (tra-BEK-ū-lē) Struts that form in response to stress in spongy bone.
trachea The main trunk of the respiratory tree.
tracheotomy Insertion of a temporary breathing tube in order to prevent suffocation due to a crushed larynx.
tracts Axons and/or dendrites with a common origin, destination, and function.
transcription Process of copying information from DNA to RNA.
transfer RNA (tRNA) RNA that "reads" mRNA at the ribosome, one codon at a time.
transgenic Type of organism with a gene or group of genes in its genome that was transferred from another species or breed.
translation Conversion of information from one language to another.
transport protein Protein that assists in facilitated diffusion.
treppe (trep') The increased strength of contraction after successive identical stimuli.
tricuspid The valve between the right atrium and right ventricle, composed of three points (cusps) of connective tissue.
trimester One of three 3-month periods during pregnancy.
trophic level All the organisms that occupy the same energy tier in a community, such as primary producers, primary consumers, or secondary consumers.
trophoblast (TRŌF-ō-blast) The superficial covering of cells of the blastocyst.
trypsin Pancreatic enzyme that digests proteins.

tubal ligation Surgical procedure that blocks fallopian tubes, preventing union of sperm and egg.
tuberculosis Disease caused by *Mycobacterium tuberculosis* infection.
tumor A group of cancer cells.
turgor Internal pressure in living cells.
tympanic (tim-PAN-ik) **membrane** A thin, semitransparent partition of fibrous connective tissue between the auditory canal and the middle ear; eardrum.
tympanic canal The lower compartment of the cochlea, continuous with the round window, where sound waves are released from the fluid of the inner ear.

ulcers Open wounds that remain aggravated in the GI tract.
ultrasound examination Bouncing ultrasonic waves through the maternal skin into the uterus to observe the reflected patterns.
umbilical cord The flexible cord that connects the fetal circulatory system with the placenta.
unstable angina Pain that develops in the heart seemingly randomly, with no connection to activity or situation.
upper respiratory tract Respiratory organs in the face and neck.
ureter (Ū-rē-ter) One of two tubes that connect the kidney with the urinary bladder.
urethra (ū-RĒ-thra) The duct from the urinary bladder to the exterior of the body that conveys urine in females and urine and semen in males.
urinalysis (ū-ri-NAL-i-sis) An analysis of the volume and physical, chemical, and microscopic properties of urine.
urinary (Ū-ri-ner-ē) **bladder** A hollow, muscular organ situated in the pelvic cavity that stores urine until it is excreted through the urethra.
urine The fluid produced by the kidneys that contains wastes and excess materials.
urogenital Concerning both the urinary and reproductive systems.
uterus (Ū-te-rus) The hollow, muscular organ in females; site of menstruation, implantation, development of fetus, and labor.
utricle (Ū-tri-kul) The larger of the two divisions of the membranous labyrinth located inside the vestibule of the inner ear, containing a receptor organ for static equilibrium.
uvula The tab of soft tissue that hangs down in the back of the throat, visible as a pointed tab.

vagina (va-JĪ-na) A tubular organ leading from the uterus to the vestibule.
vagus nerve Cranial nerve X that innervates the muscles of the throat, and thoracic and abdominal organs.
valence shell A group of electron orbitals around the nucleus.
van der Waals force Weak interaction between resonating molecules.
variable A factor that can be changed in an experiment to test whether and how it affects the outcome.
varicose veins A medical condition in which superficial veins fill with blood but do not empty, resulting in a distended, often painful swelling on the surface of the body.
vegan A vegetarian who consumes only plant products, eating no animal products whatsoever.
vein A blood vessel that carries blood from tissues back to the heart.
vena cavae (VĒ-na CĀ-vē) The two large veins that open into the right atrium, returning to the heart all of the deoxygenated blood from the systemic circulation except that from the coronary circulation.
ventral cavity Entire ventral aspect of torso; belly and chest.
ventricle (VEN-tri-kul) A cavity in the brain filled with cerebrospinal fluid. An inferior chamber of the heart.
venules Small veins that drain blood from capillaries to larger veins.
vertebrae Bony structures that comprise the vertebral column.
vertebral (VER-te-bral) **body** The vertebra, exclusive of the vertebral arch.
vestibular (ves-TIB-ū-lar) **canal** The uppermost compartment of the cochlea, continuous with the oval window, where sound waves travel on their way to the auditory nerves.
vestibulocochlear (ves-tib′-ū-lō-KOK-lē-ar) **nerve** Cranial nerve VIII that carries impulses from the ear to the brain.
viable Capable of remaining alive.
villi (VIL-ī) Finger-like digestive extensions from intestinal mucosal cells. Singular is villus (VIL-lus).
visual acuity The resolving power of the eye.
vital capacity (VC) The sum of inspiratory reserve volume, tidal volume, and expiratory reserve volume.
vitreous (VIT-rē-us) **humor** A gel-like fluid that holds the third tunic, the retina, in place.
vocal folds A pair of cartilaginous cords stretching across the laryngeal opening that produce the tone and pitch of the voice; vocal cords.
voltage-regulated Describes membrane channels that open or close in response to changes in the transmembrane electrical charge (membrane potential), of the cell.

water potential Osmotic pressure of resting cells in an isotonic solution; equals pressure from the environment plus the cell's solute concentration.

yolk sac A structure that provides some nutrition to the embryo.

zona pellucida (pe-LOO-si-da) A gel-like layer surrounding the maturing oocyte.
zooplankton Microscopic and macroscopic animals that float in the water column and move at the mercy of the currents.
zygote (ZĪ-got) The cell resulting from the union of male and female gametes; the fertilized ovum.

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