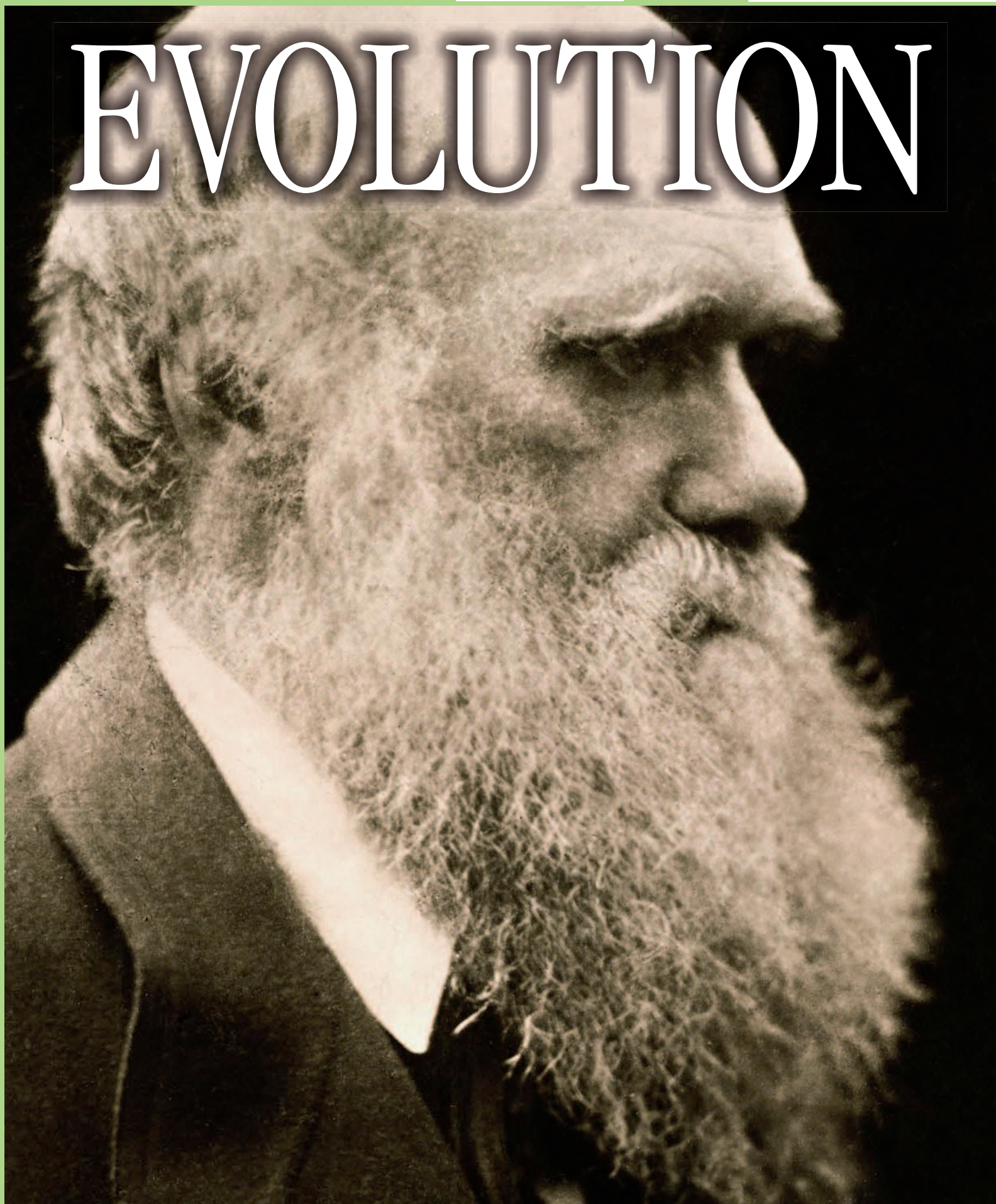
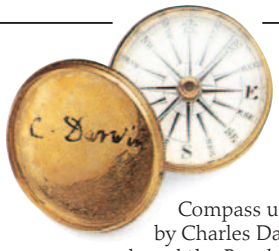
DK Eyewitness

EVOLUTION



Eyewitness
Evolution


Snails with feelers extended
Skull of early hominid *Homo erectus*
Rock containing fossilized remains of several species of trilobite
Duck-billed platypus
Fossilized skeleton of *Procynosuchus*, a mammal-like reptile
Skull of modern human
Rock composed of millions of seashells



Compass used by Charles Darwin aboard the *Beagle*

Butterfly wing from Charles Darwin's collection

Eyewitness Evolution

Written by
LINDA GAMLIN

Froglets

South American *Agrias claudina* butterfly

Bee orchid

DK Publishing

"Hand" and "finger" bones of horse's leg

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19th-century microscope

Beetles

Bones of armadillo's forelimb

Bones of dolphin's flipper

Contents

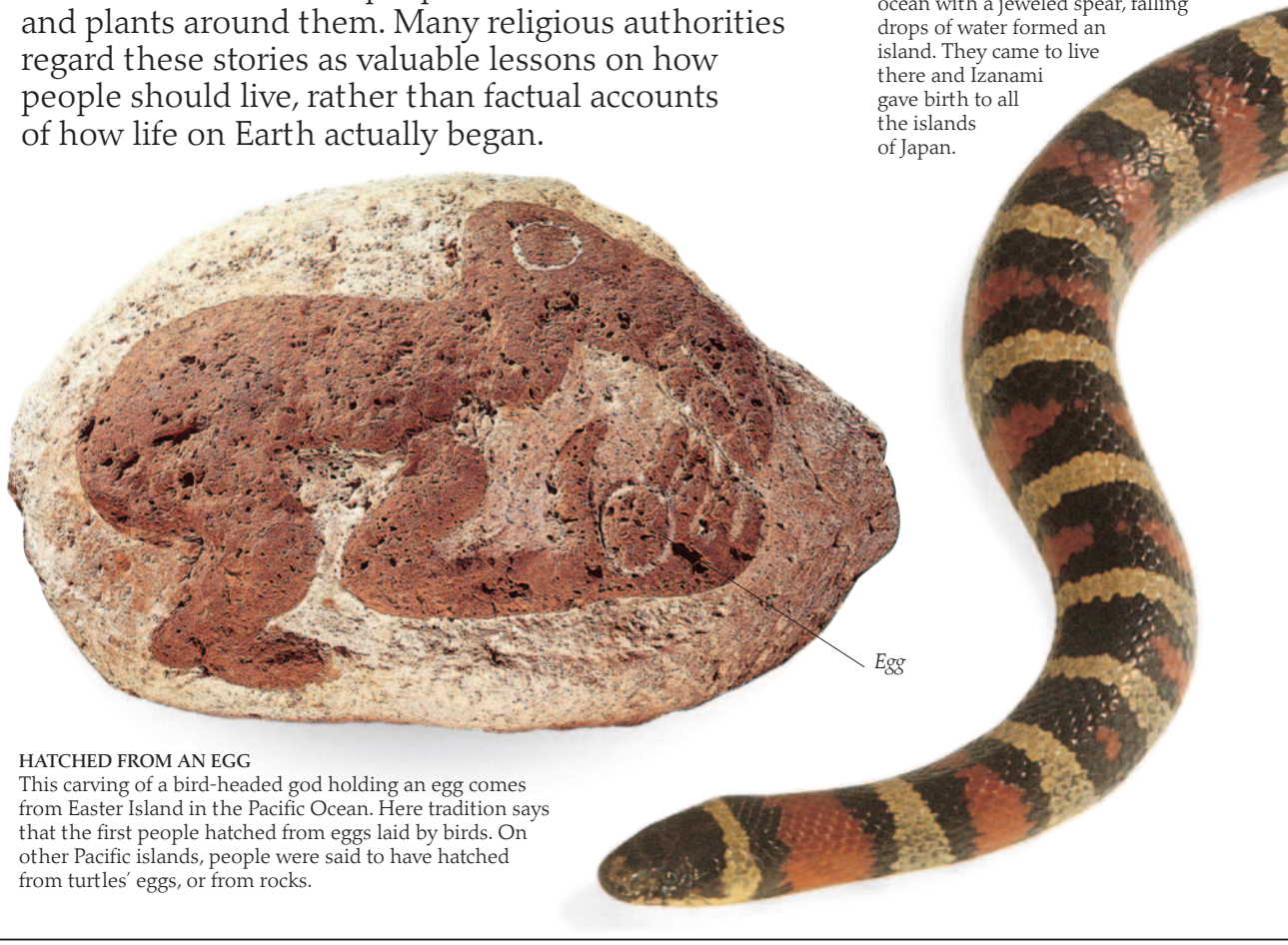
Members of the insect order Hemiptera

Creation stories

Where do people come from? How did the world begin? Where do plants and animals come from? People have been thinking about these questions for thousands of years, and there are many answers in the form of traditional stories. Some of these stories tell of a god who created the world and everything in it, including people. Other stories have many gods, who each made different things and then fought great battles for control of the world. Not all stories describe the world as having been created, however. Some tell of the world growing out of nothing, or out of chaos, without any creator. According to Buddhist beliefs, there was no beginning: instead, the universe goes through endless cycles of being and nonbeing. The stories are all very different, but they often try to explain certain things about life. Some explain why people get sick and die, or why there is night and day. They may also explain some minor features of living things, such as why snakes have no legs. More importantly, the stories often give people rules or guidelines for their lives. They may say something about the different ways in which men and women should behave, or how people should treat the animals and plants around them. Many religious authorities regard these stories as valuable lessons on how people should live, rather than factual accounts of how life on Earth actually began.

IN THE BEGINNING
These 16th-century illustrations show the Biblical creation story, which Christians and Jews share. There are two versions of the story, both in the first book of the Bible, Genesis. In the first version, shown here, man and woman are made simultaneously on the sixth day of creation. In the second version of the story, God creates the first man, Adam, before any other living thing. He then plants the Garden of Eden and makes all the animals. His final act is to create the first woman, Eve.

CREATORS OF THE WORLD
The Japanese creation story tells that in the beginning there were eight gods. When the youngest two, Izanagi and Izanami, stirred the ocean with a jeweled spear, falling drops of water formed an island. They came to live there and Izanami gave birth to all the islands of Japan.



HATCHED FROM AN EGG
This carving of a bird-headed god holding an egg comes from Easter Island in the Pacific Ocean. Here tradition says that the first people hatched from eggs laid by birds. On other Pacific islands, people were said to have hatched from turtles' eggs, or from rocks.

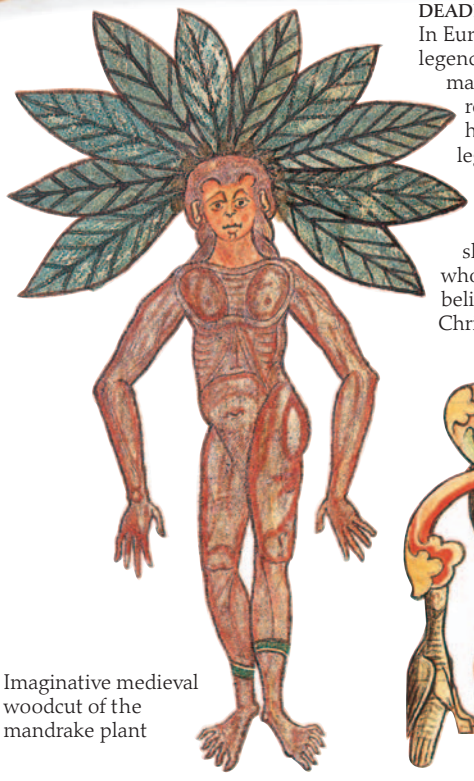
Humans cling to Tangaroa's body

MAKER OF HUMANKIND
Carved by the people of Rurutu Island in the Pacific, this statue of the god Tangaroa is covered in tiny people that he has created. The same god appears in myths from other Pacific islands, but in some of these he is just one god among many and not the creator.

FROM THE FIRE
In addition to the great creation stories, there have always been minor legends explaining the origins of plants and animals. In Europe, salamanders were said to be born from flames. Salamanders do hide among damp logs and may have been seen rushing out from the flames of log fires.

Illustration from the Middle Ages, showing a salamander rising from the flames

EXPLAINING THE WORLD
The Biblical Genesis story explains, among other things, why snakes have no legs. God forbade Adam and Eve to eat from the tree of knowledge of good and evil, but a serpent tempted Eve to eat the fruit. As a punishment, the serpent was told: "Upon thy belly shalt thou go and dust shalt thou eat."

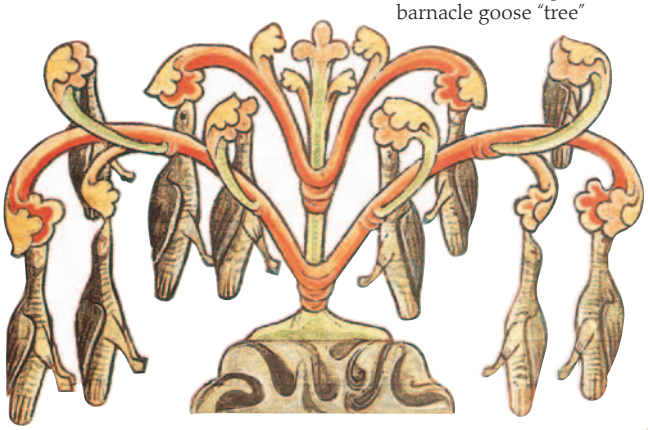


Imaginative medieval woodcut of the mandrake plant

DEADLY SCREAM
In Europe, one minor legend concerned the mandrake plant, whose roots are sometimes human-shaped. The legend claimed that mandrake roots cried out when pulled from the ground, and this shriek would kill anyone who heard it. This pagan belief survived into Christian times.

CHANGING FORMS
Stalked barnacles are often seen attached to driftwood. In medieval times, they were said to grow on trees and then to turn into barnacle geese that flew away. Scientific study of the living world, from the 16th century on, cast doubts on such legends, and careful observation gradually took their place.

Medieval drawing of barnacle goose "tree"

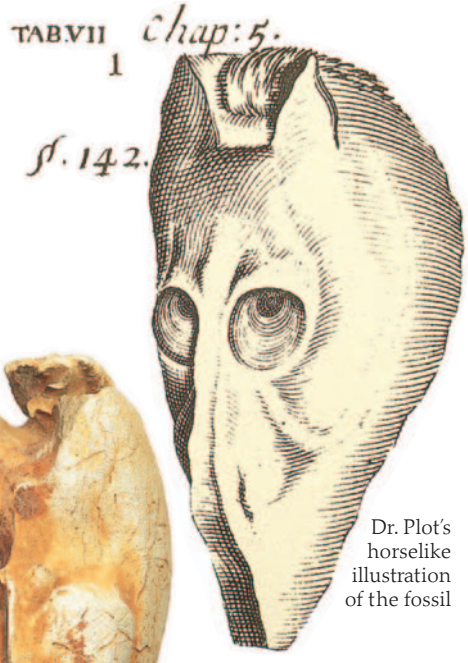


Stalked barnacles on driftwood

Fossils and fairy tales

ELFIN FARE
Thinking they were fairy loaves, people in southern England kept fossil heart urchins like this in their pantries to ensure that there would always be bread for the family.

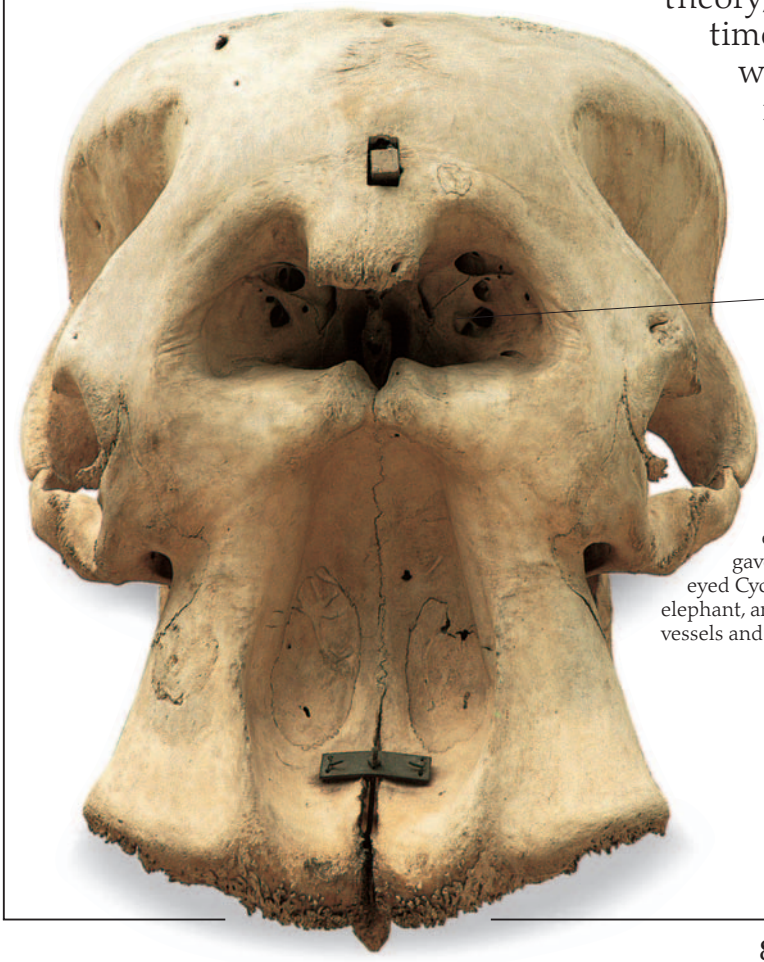
FOSSILS ARE THE REMAINS or impressions of living things hardened in rock. People have been finding fossils for at least 30,000 years. Ice Age hunters made them into necklaces, and the idea that fossils had magical properties may well have begun then. Magical beliefs about fossils became common all over the world. The Chinese kept tiny fossilized fish in their food pantries to keep away insect pests called silverfish. The Roman scholar Pliny the Elder wrote that fossilized sea urchins could cure snakebites and ensure success in battle. He also collected some extraordinary "tall tales" to explain the origins of fossils: sea urchin fossils were said to be formed from balls of foam created by masses of entwined snakes. Other people developed theories to explain fossils in general. One idea was that the rain picked up the seeds and eggs of living things from the sea. When the rain fell and seeped into rocks, the seeds and eggs grew into stony replicas of their true selves. This was an attempt to explain why so many fossils are clearly sea creatures. A more fanciful theory, popular from medieval times until the 17th century, was that Earth had its own "creative force," or *vis plastica*, and this force was trying to make copies of living things.



Dr. Plot's horselike illustration of the fossil

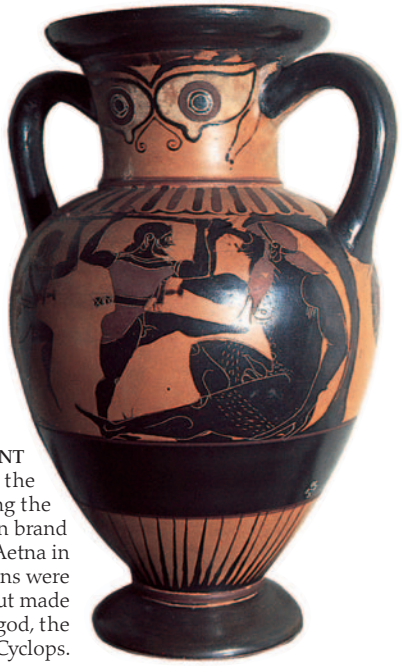
Fossil mold

STONE HORSES
This unusual fossil is the cast, or mold, of the inside of a shell called *Myophorella*. The shell itself has dissolved away. The living animal was similar to an oyster, having two shells held together by a strong muscle. This left a circular mark on each side, and Dr. Robert Plot (1640–1696) interpreted these as eyes. With great imagination, he also saw two ears and a mane and declared that this was an attempt by Earth's *vis plastica* to make a horse's head.

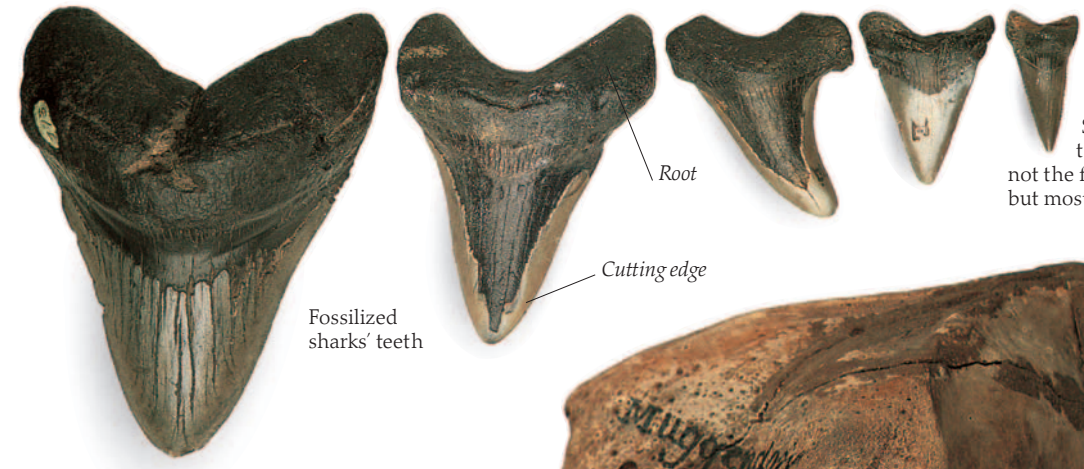


Opening in skull for trunk

ONE-EYED MAN
When skulls like this were found in fossil form on the Mediterranean island of Sicily, the ancient Greeks imagined giant men, each with a single eye in his forehead. This belief gave rise to the legend of the one-eyed Cyclops. In fact, this is the skull of an elephant, and the hole is where its blood vessels and airways ran down to the trunk.



BLINDING THE GIANT
On a vase from ancient Greece, the hero Odysseus is shown blinding the Cyclops Polyphemus with an iron brand as he sleeps in his cave on Mount Aetna in Sicily. Odysseus and his companions were able to escape from the island but made an enemy of Poseidon the sea god, the father of the Cyclops.



Fossilized sharks' teeth

TONGUES FROM THE SKY
Pliny the Elder believed that these fossils were stone tongues that fell to Earth during eclipses of the Moon. In 1667 Niels Stensen dissected a dead shark and realized that they were simply sharks' teeth. He was not the first with a sensible explanation for fossils, but most people preferred the tall tales.

MYTHICAL MONSTERS
During the last ice age 40,000 years ago, there were giant bears in Europe. Some died in caves while hibernating, and many were fossilized because the cool dark cave environment helped preserve their skeletal remains along with footprints and claw marks. When the skulls of these bears, with their huge canine teeth, were found in the Middle Ages, they were thought to belong to fire-breathing "dragons."

Cave bear skull

Drawing of ammonite

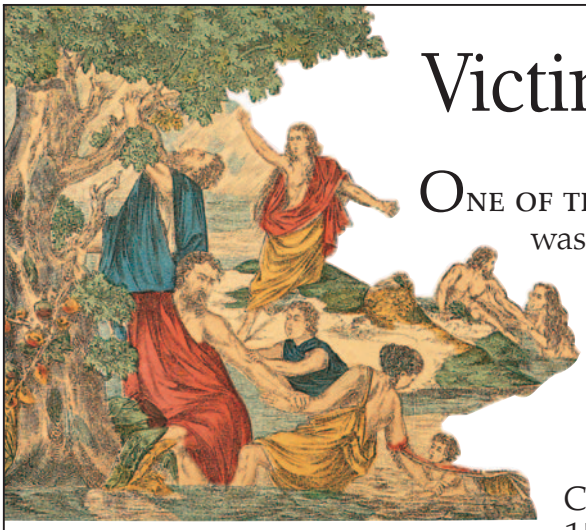
SERPENTS OF STONE
In northern England the coiled fossils of ancient ammonites, sea animals like the living *Nautilus*, were once thought to be snakes that had been turned to stone by a saint. Local people even carved heads on to these "snake stones," just to prove the point.

Mythical winged dragon

FOSSIL FUNGUS?
Despite its toadstool-like appearance, this strange object is actually a sponge from an ancient sea. The sponge has become fossilized in flint. Toadstools are too soft to become fossilized, but are rarely preserved in amber.

Fossil ammonite

Victims of the flood



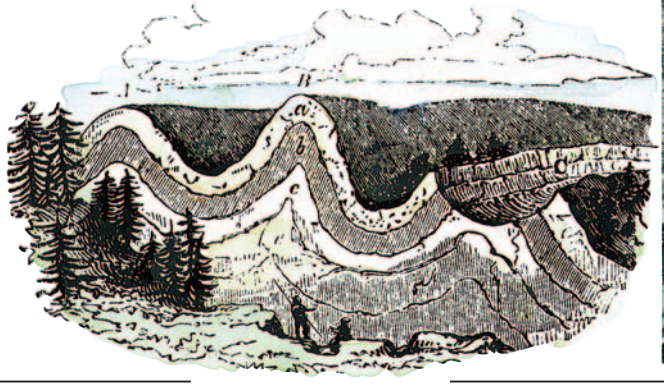
NOAH AND THE FLOOD
The Bible describes an immense flood that covered all Earth's land and lasted for 40 days. Noah had been told by God to build an ark and take on board a male and a female of every kind of animal, so that none of them would die out completely. This part of the story led to great debates when the fossils of large extinct animals were discovered (pp. 14–15).

ONE OF THE GREATEST PUZZLES about fossils was the appearance of shells and other sea creatures high up on mountaintops. Some Ancient Greek scholars, such as Pythagoras and Herodotus, reasoned that such mountain rocks must once have been under the sea, but the early Christian philosopher Tertullian (around 155–222 CE) claimed that the waters of the flood, as described in the Bible, had carried shells up to this height. This idea was considered by Leonardo da Vinci (1452–1519), who made careful observations of fossils and calculated what would happen during a massive flood. He concluded that the explanation made no sense. Despite Leonardo's efforts, the idea was popular among geologists until the late 18th century. By then the theory was known as diluvialism. It proposed that all Earth's sedimentary rocks (made of sand, mud, and lime) had been deposited by floods when all the victims had been drowned and preserved as fossils within them. As a popular notion, rather than a scientific theory, it survived among fundamentalists into the 19th century, but by 1820 the evidence against it was so strong that the idea had largely disappeared.

Shelly rock from the top of Mount Snowdon in Wales

FOSSIL HUNTER
Johann Scheuzer (1672–1733), a Swiss fossil collector, was an enthusiastic "diluvialist"—one who believed that the flood had created all sedimentary rocks and fossils. He described one of his finds as "the bony skeleton of one of those infamous men whose sins brought upon the world the dire misfortune of the deluge." It was a fossil of a giant salamander.

RAISING THE ROCKS
During the 18th and 19th centuries, geologists began to understand how sea shells could appear on mountaintops. They realized that most sedimentary rocks had been deposited in the sea as sand, mud, and lime. Here the remains of dead organisms were buried and fossilized as the sediment turned to rock. Later Earth movements squeezed and broke the rocks, buckling them into folds, so that rocks that had been under the sea were raised into mountains.



The missing fossils

If all fossils were creatures killed by the flood, there would be fossils of a great many land animals that were drowned as the waters rose, but few fossils of fish, since they could swim. In fact, the opposite is true. Seafloor creatures are some of the most common fossils, while land animals are relatively rare. However, land environments such as swamps and lakes, and their life are sometimes fossilized.

Rare fossil of an insect

Uncommon dragonfly fossil

Lizard

RARELY FOSSILIZED
While fossils of seabed-dwelling creatures such as clams and snails are often found, insects, lizards, and marine brittle stars are rare.

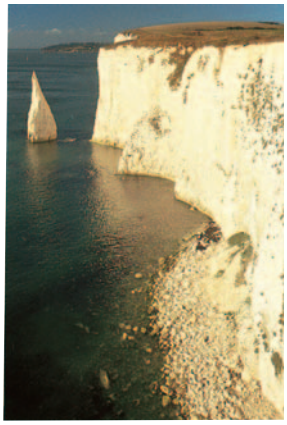
Fossilized brittle star, a marine animal

SHELLY ROCK
Some rocks are made entirely of rapidly deposited shells. Others, like coal and chalk, built up very slowly.

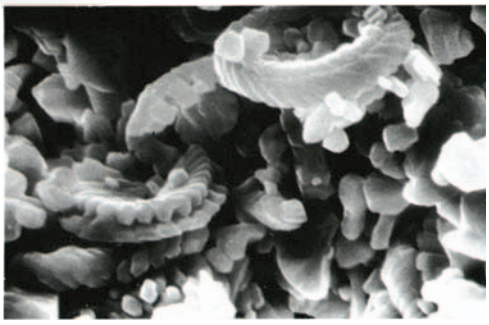
Fossil perch

Chalk and coal

As people learned more about sedimentary rocks, it became clear that these cannot all have been laid down in a few years. Chalk and coal, for example, are made up of the remains of living things—trillions of microscopic shells, in the case of chalk, and thousands of plant remains piled one upon another for coal. Clearly, such rocks must have taken a very long time to build up.



ROCK OF AGES
In 1858 a geologist, looking at chalk under the microscope, found that it was almost entirely made up of tiny shells. These shells belonged to microscopic creatures that floated at the ocean's surface. We know this because their relatives still do so today. Chalk cliffs (above) show how thick the layers of chalk are.



MICROSCOPIC STRUCTURE
When chalk is imaged under an electron microscope, its structure reveals that it is made up almost entirely of the calcareous (calcium-rich) skeletons of minute creatures.

Fern fossil in coal

THE COAL FORESTS
Coal is made almost entirely of plant remains from bogs and swampy forests. When the plants died, their tissues did not rot away but gradually turned into peat. This was then compressed by the growing weight above it, turning it into coal. Coal seams can be 65 ft (20 m) thick.

REVOLUTIONARY THINKER
French naturalist Lamarck made people think about evolution.

Jean-Baptiste de Lamarck

Jean-Baptiste de Lamarck (1744–1829) was one of the first people to propose a theory of evolution. He believed that there were two evolutionary forces at work. The first was a "tendency to progression," an automatic process by which all living things became more complex. The second force was the need to fit in with the local environment: as animals tried to fit in, their efforts produced a bodily change. In this way the giraffe developed a long neck by stretching for the leaves of trees, and wading birds grew long legs by straining upward to keep themselves dry. These two forces were not in harmony, according to Lamarck. The first force working alone would produce perfect patterns of increasing complexity among animals, but the second force interfered with the first. For the second force to work, characteristics acquired by the parents (such as a longer neck) would have to be passed on to their offspring. This is now known not to happen, except in a few rare cases, but in Lamarck's day it was a common idea. For a century afterward, everyone, including Darwin (p. 20), believed it to be true. Today, the term "Lamarckism" is often used just to mean the inheritance of acquired characteristics. The other parts of Lamarck's theory have largely been forgotten.

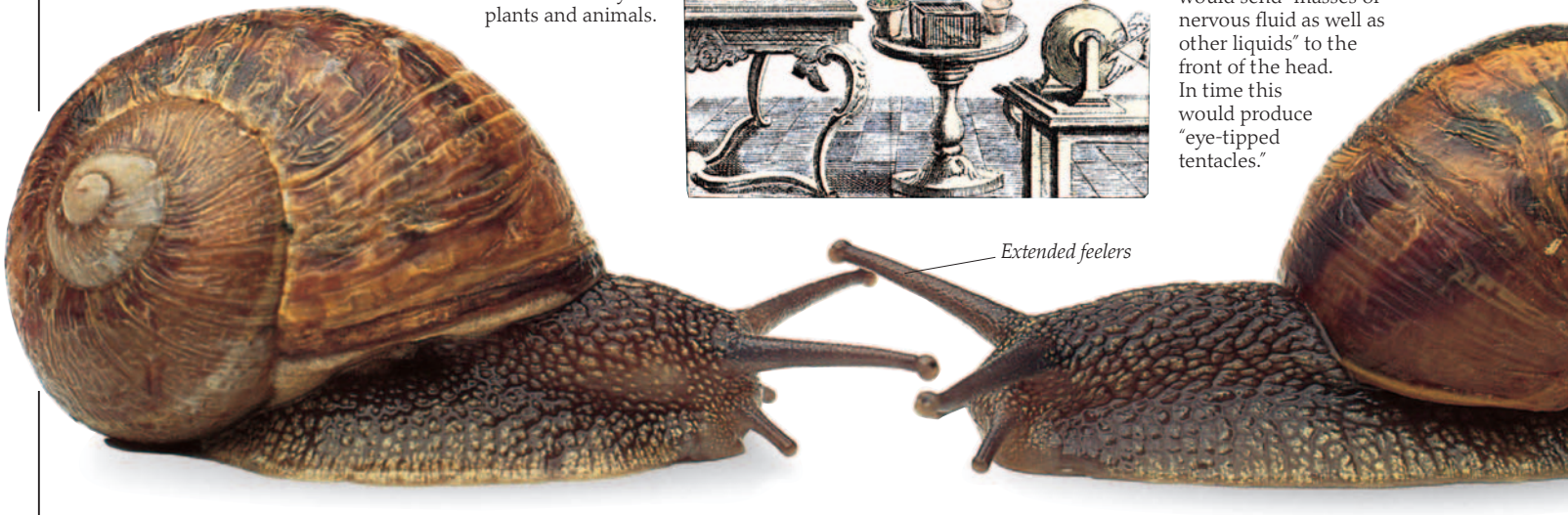
HIGH AND DRY
According to Lamarck's theory, by trying to keep its belly out of the water a wading bird "acquires the habit of stretching and elongating its legs." In this way, he believed, species such as this purple heron developed their long legs.

Subtle fluids

Lamarck suggested that there were "subtle fluids" flowing all around a body and all through it, and that these produced both movement and change. He regarded the fluids as mysterious, but believed he could identify two: caloric (heat) and electricity.

CHARGED IDEAS
Lamarck believed that his "subtle fluids" were involved in both kinds of change—the "tendency to progression" and the striving to fit local conditions. Electricity was of great interest to scientists at the time, and it appealed to Lamarck because it could be felt but not seen. The French scientist Jean-Antoine Nollet (1700–1770) set up experiments (right) to study the effects of static electricity on plants and animals.

FEELING THE WAY FORWARD
Lamarck used snails as an example of how "subtle fluids" worked. Snails have poor vision, and he imagined an ancestral snail with no feelers, groping around with its head. Its efforts to feel the way would send "masses of nervous fluid as well as other liquids" to the front of the head. In time this would produce "eye-tipped tentacles."



Looking at the evidence

To support his claim that evolution had occurred, Lamarck pointed to the way that members of a species, such as a butterfly species, can vary from place to place. His ideas about the inheritance of acquired characteristics and about the continuous creation of simple life forms were later proven to be false.

Agrias claudina sardanapalus
Peru and Brazil

Agrias claudina claudina
Eastern Central Brazil

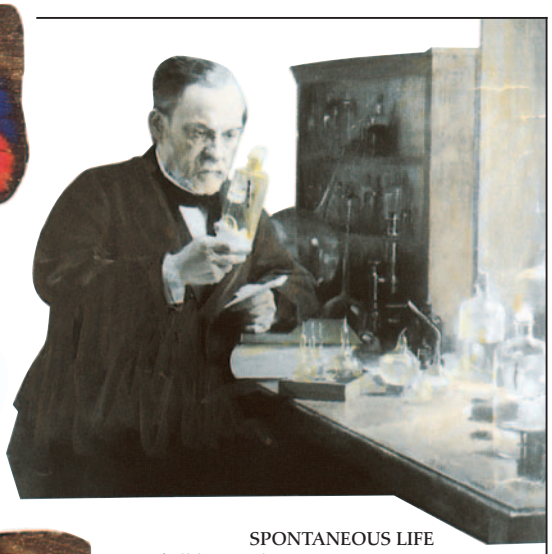
Agrias claudina lugens
Peru

Agrias claudina claudianus
Southeastern Brazil

Agrias claudina godmani
Central Brazil

MAKING NEW SPECIES
These lovely butterflies from different areas of South America illustrate Lamarck's point about variation within a species. Those from different areas can all interbreed, so they must all belong to the same species. They are called "subspecies." Lamarck also observed that closely related species (p. 22) can look very much alike, as similar as these subspecies. From this he concluded that related species had developed from a set of subspecies. This idea is now thought to be correct, although exactly how new species are formed is still being debated (p. 40).

Agrias claudina intermedius
Southeastern Colombia, Venezuela

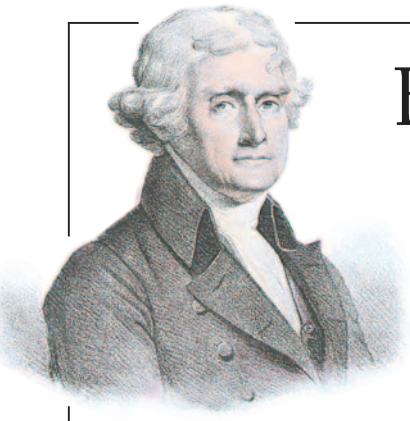


SPONTANEOUS LIFE
If all living things are progressing, why are there still simple creatures left? Lamarck believed that new ones arose by "spontaneous generation" of microscopic life from nonliving matter, such as wet straw. French microbiologist Louis Pasteur (1822–1895) showed this to be an illusion. If the straw was boiled thoroughly, no living things developed.

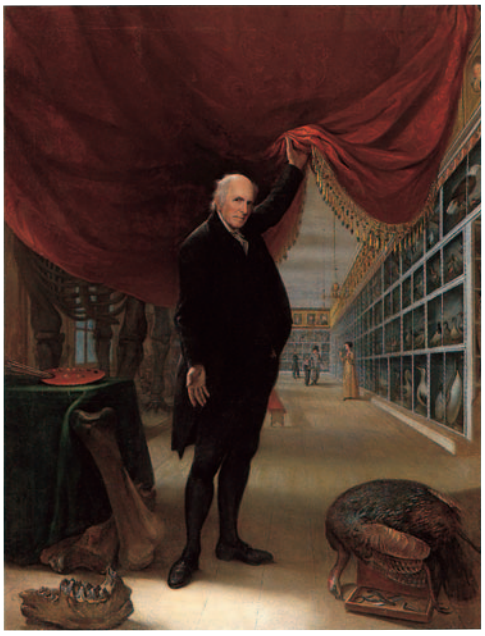
PASSING IT ON
If acquired characteristics were inherited, as Lamarck thought, then the children of white-skinned people living in hot countries would be born with sun-tanned skins. This English family in 19th-century India shows that they are not.

POET AND BOTANIST
Even before Lamarck, the poet Johann Goethe (1749–1832) had published evolutionary ideas about plants.

Extinct animals



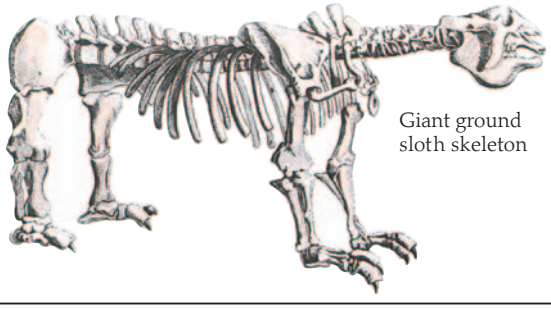
SCIENTIFIC PRESIDENT
US President Thomas Jefferson (1743–1826) was also a fossil collector. At first he could not accept that any animal had become extinct, but in time the evidence of the fossil finds convinced him that they had.



According to the Bible, Noah took two of every kind of animal into his ark, and all survived the Flood. Christianity also taught that each living thing was an essential link in God's chain of creation. Thus, it would be impossible for any of them to have died out completely, or become "extinct." When fossils of unknown creatures were found, it was assumed that the animals were still living somewhere in the world. However, by the end of the 18th century, the fossils of such gigantic creatures had been found that this explanation began to seem unlikely. In North America the massive bones of the giant ground sloth and the mastodon were discovered. No unexplored regions were large enough to hide such giants, and the suspicion that they had become extinct began to grow. French scientists, less influenced by religious views following the upheavals of the French Revolution, were among the first to accept the idea of extinction. Afterward, the idea was accepted in the US, and then, more slowly, in other countries.

LOST WORLDS
The strange duck-billed platypus of Australia was only discovered by western science in 1799. Discoveries like this suggested that there were many unknown creatures in the world and that "extinct" animals could still be alive somewhere.

HARD TO HIDE
This is a cross-section, shown half life-size, through the upper molar teeth of a giant ground sloth, known as *Megatherium*. The fossils of another ground sloth, almost as large, were found in North America and first described by Thomas Jefferson in 1797. A living animal of this size could clearly not remain undiscovered, unlike small animals such as the platypus. By the 1830s the idea of extinction had become widely accepted.



Giant ground sloth skeleton

Human second molar tooth

PEALE'S MUSEUM *(left)* Charles Willson Peale (1741–1827) was an artist, showman, and fossil collector. In 1799, together with Jefferson and others in the American Philosophical Society, he advertised for large fossil bones. In this way he was able to locate and excavate the skeletons of two mastodons, extinct relatives of the elephants. The bones were mounted to make a complete skeleton, and Peale displayed this in his museum of "natural curiosities."

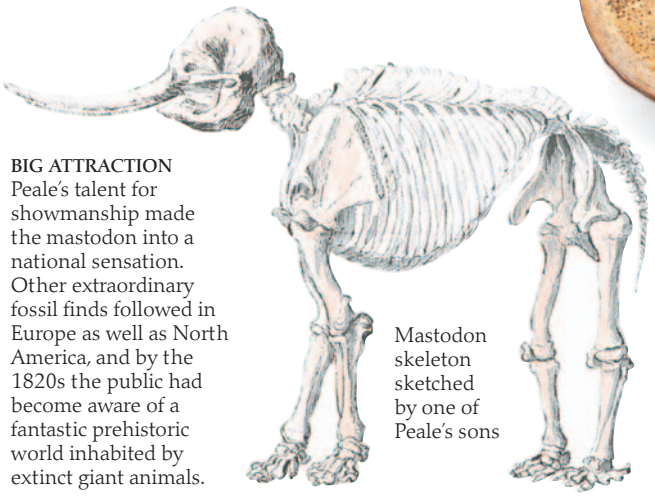
GIANT MOLAR The second molar tooth of the mastodon, complete with its root, dwarfs a molar tooth from a human mouth. Giant mammals such as the mastodon were discovered before the first dinosaurs came to light. When the even larger remains of the dinosaurs were found, beginning in the 1820s (p. 18), the idea of extinction became widespread.

Second molar tooth of a mastodon

OUT OF THE PIT Peale's mastodon skeleton was found in swampy ground, and the excavation was difficult. He had to design a machine to bail out the water from the pit. This was operated by a large treadwheel, and the tourists who flocked to see the excavation were put to work operating the wheel. Peale himself painted this dramatic picture of the scene, and Americans became intensely proud of their extinct giants.

Human vertebra

Mastodon vertebra



BIG ATTRACTION Peale's talent for showmanship made the mastodon into a national sensation. Other extraordinary fossil finds followed in Europe as well as North America, and by the 1820s the public had become aware of a fantastic prehistoric world inhabited by extinct giant animals.

Mastodon skeleton sketched by one of Peale's sons

ARGUING OVER BONES A bone from the mastodon's spine (right) is huge compared with a human vertebra. The first scientific description of the mastodon was by the French scientist and antievolutionist Cuvier (p. 16). Unlike his colleague Lamarck (p. 12), he came to accept the idea of extinction. In Lamarck's theory of evolution, no living things could become extinct because they all automatically progressed and adapted to their environment.

A series of catastrophes

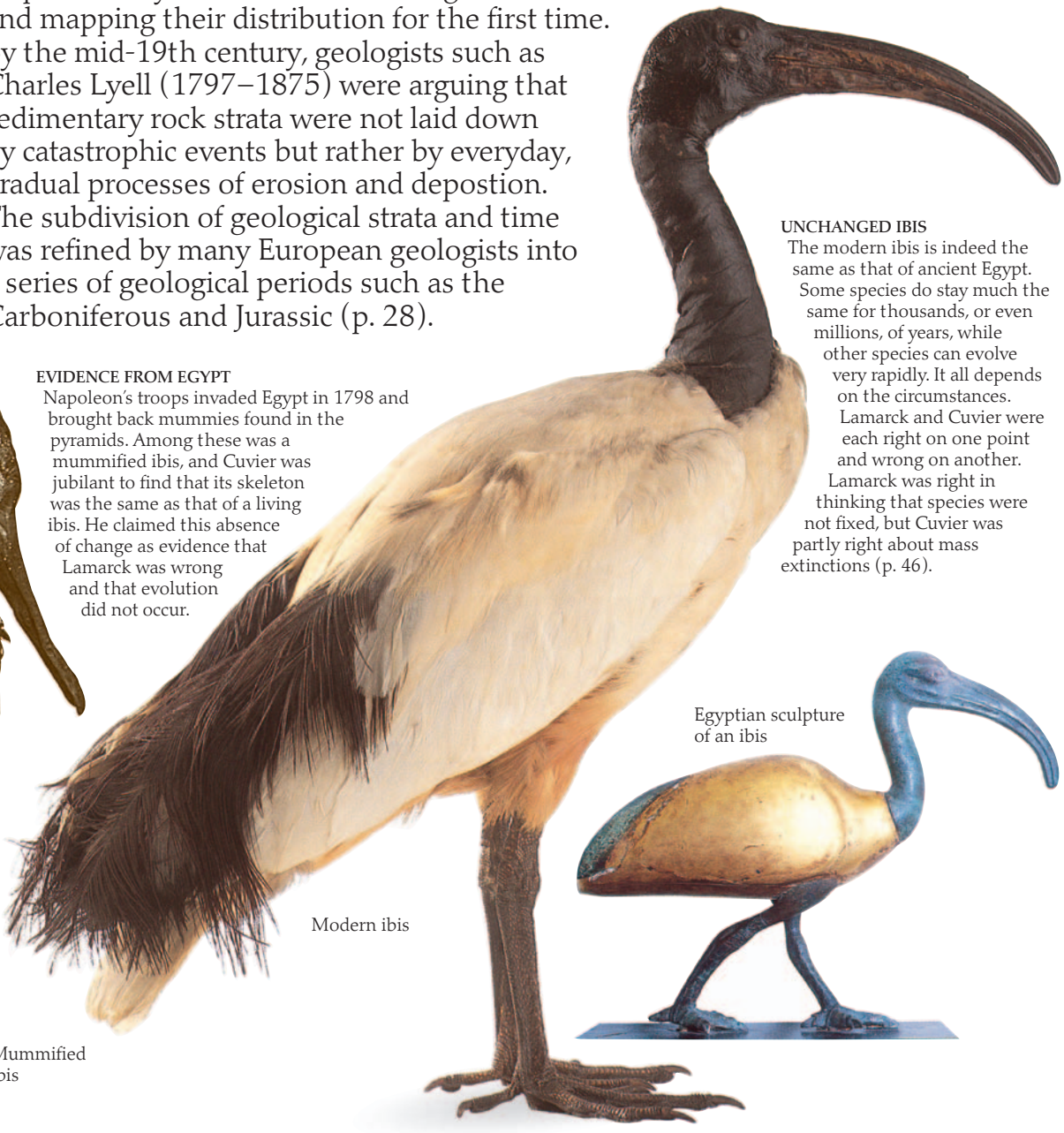
GEORGES CUVIER
Cuvier believed that catastrophes had stripped much of Earth of life several times, but that some regions had always escaped, and animals had spread again from those regions. Later he also accepted that some animals had become extinct, while Lamarck refused to believe this. Cuvier was against evolution, believing that life had "stood still" between catastrophes. Lamarck and Cuvier became life-long enemies.

INDUSTRIAL EXPANSION in the 18th century created a need for iron ore and coal, as well as canals for transportation. Mines and excavations went deep underground, which led to great advances in geology. By the late 18th century the German naturalist Abraham Werner (1750–1817) had divided rock strata into three groups—Primary, Secondary, and Tertiary, from oldest to youngest. Werner thought that all these strata had been laid down by a series of catastrophic worldwide floods. By the beginning of the 19th century, it was realized independently by William Smith (1769–1839) in England and Georges Cuvier (1769–1832) in France that fossils could be used to characterize successive strata. Cuvier also thought that successive strata resulted from a series of catastrophic floods. Nevertheless, fossils were shown to be particularly useful for subdividing rock strata and mapping their distribution for the first time. By the mid-19th century, geologists such as Charles Lyell (1797–1875) were arguing that sedimentary rock strata were not laid down by catastrophic events but rather by everyday, gradual processes of erosion and depostion. The subdivision of geological strata and time was refined by many European geologists into a series of geological periods such as the Carboniferous and Jurassic (p. 28).

UNCHANGED IBIS
The modern ibis is indeed the same as that of ancient Egypt. Some species do stay much the same for thousands, or even millions, of years, while other species can evolve very rapidly. It all depends on the circumstances. Lamarck and Cuvier were each right on one point and wrong on another. Lamarck was right in thinking that species were not fixed, but Cuvier was partly right about mass extinctions (p. 46).

EVIDENCE FROM EGYPT
Napoleon's troops invaded Egypt in 1798 and brought back mummies found in the pyramids. Among these was a mummified ibis, and Cuvier was jubilant to find that its skeleton was the same as that of a living ibis. He claimed this absence of change as evidence that Lamarck was wrong and that evolution did not occur.

Mummified ibis

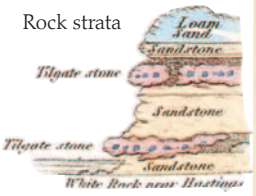


Modern ibis

Egyptian sculpture of an ibis

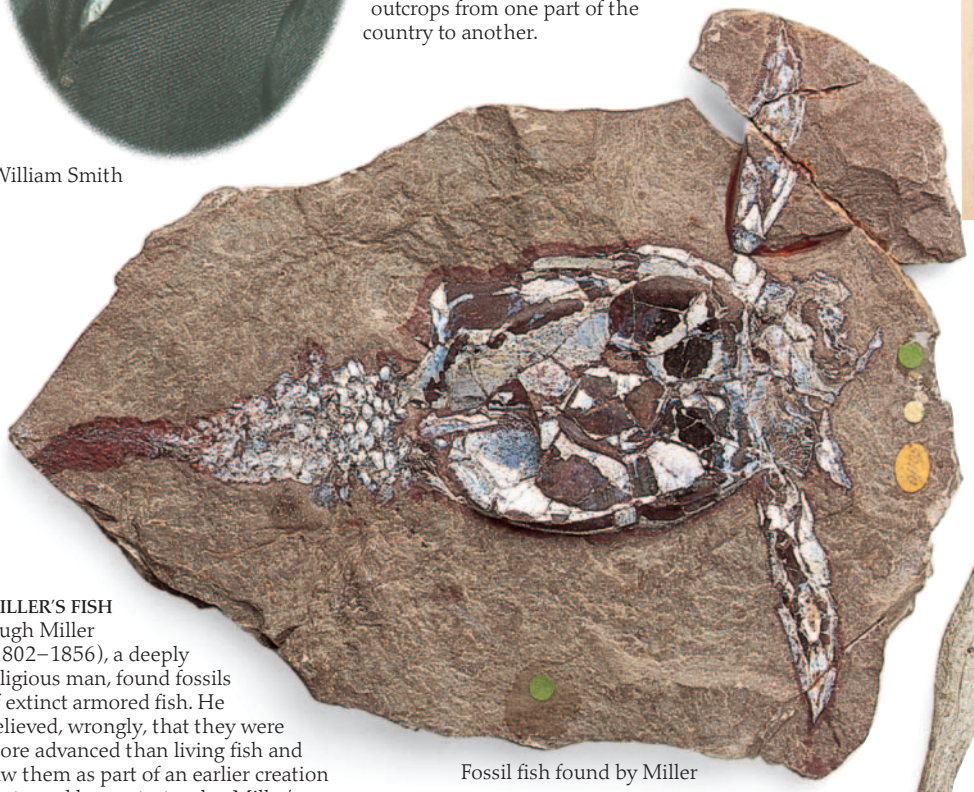
William Smith

CLUES FROM CANALS
From childhood William Smith collected fossils, and later developed a professional interest in rocks and fossils while working as an engineer and surveyor on the construction of canals. He found that successive strata could be characterized by their fossils and always occur in the same sequence. This allowed him to identify and map the succession of strata across the landscape matching otherwise separate outcrops from one part of the country to another.



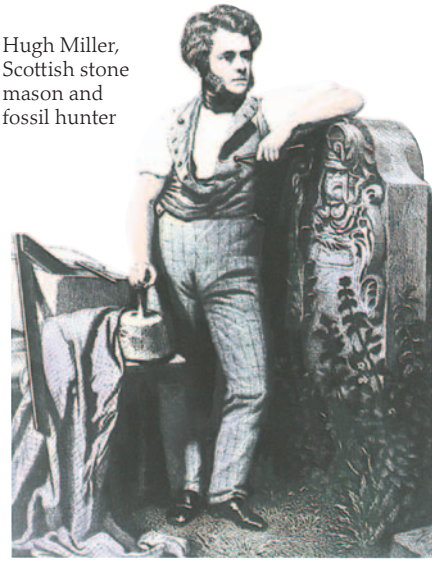
Rock strata

One of Smith's geological maps showing strata as different colors



Fossil fish found by Miller

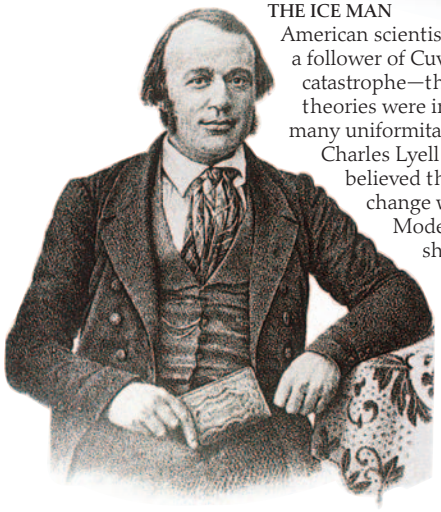
MILLER'S FISH
Hugh Miller (1802–1856), a deeply religious man, found fossils of extinct armored fish. He believed, wrongly, that they were more advanced than living fish and saw them as part of an earlier creation destroyed by a catastrophe. Miller's books, trying to reconcile geology with the Bible, were very popular.



Hugh Miller, Scottish stone mason and fossil hunter

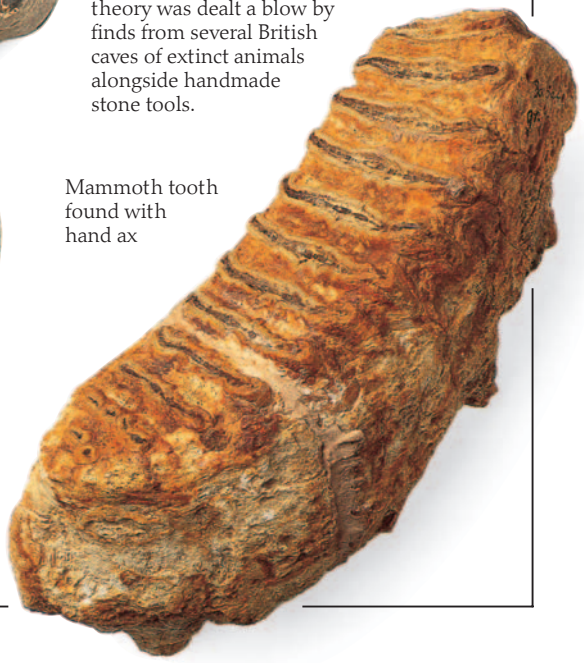
CONTROVERSIAL FINDS
Miller helped to popularize a new religious version of catastrophe theory. It held that there had been several successive creations, each destroyed by a catastrophe, and that the Bible told only of the last creation. All fossils of extinct animals were from earlier creations. This theory was dealt a blow by finds from several British caves of extinct animals alongside handmade stone tools.

Miller's paper model of extinct fish



THE ICE MAN
American scientist Louis Agassiz (1807–1873), a follower of Cuvier, added a new type of catastrophe—the Ice Ages. Agassiz's theories were initially rejected by many uniformitarians, such as Charles Lyell (1797–1875), who believed that all geological change was gradual. Modern geology has shown that both processes are at work. There are gradual and generally predictable processes. Then there are less predictable events on different scales, such as catastrophic earthquakes, storms, tsunamis, extra-terrestrial impacts, ice ages, and rapid climate change.

Hand ax made by early people



Mammoth tooth found with hand ax

Dinosaur frenzy

DIGGING FOR *IGUANODON*
Excavations at the quarry in Sussex, southern England, from which Gideon Mantell's *Iguanodon* teeth originally came.

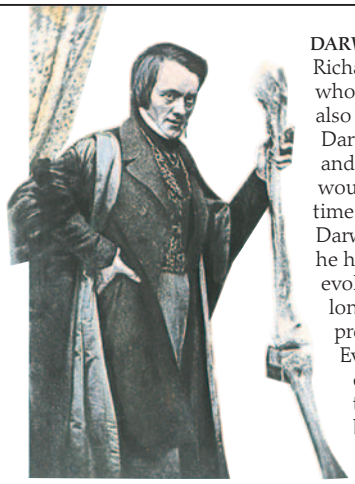
FOSSILIZED DINOSAUR BONES were discovered as early as the 17th century, but they were not recognized as giant reptiles. The breakthrough came with Gideon Mantell (1804–1892), a British doctor and fossil hunter. In 1822 he found some large and unusual teeth that he showed to Cuvier (p. 16) and William Buckland, a British geologist. Both dismissed them as unimportant, but Mantell was convinced they were wrong and continued his research. Eventually he found that the teeth resembled those of iguana lizards. Calling his find *Iguanodon* (iguana-tooth), he published a description of a lizard 40 ft (12 m) long. In the meantime, Buckland had found his own giant reptile. Such finds continued, but the name dinosaur ("terrible lizard") was not used until 1841, when it was coined by Richard Owen, a celebrated anatomist and follower of Cuvier. Dinosaurs created a sensation because they were so spectacularly different from anything still alive. They remained headline news throughout the 19th century, making everyone aware of the distant past and its strange animals. This awareness set the stage for evolutionary ideas. Yet Owen used the dinosaurs as an argument against evolution, claiming that they were more advanced than living reptiles. Modern evolution theory recognizes that evolution does not always mean progress (p. 48). If the environment changes, more advanced animals can die out while their less advanced relatives survive.

SURPRISING FINDS
William Buckland (1784–1856) displays some prize specimens. The long-beaked skull at the front is an ichthyosaur, a marine reptile that belonged to a separate group from the dinosaurs. The first ichthyosaur was described in 1810 but was thought to be a crocodile. In 1824 Buckland found jaw fragments and other bones of a dinosaur called *Megalosaurus*. Richard Owen supervised the making of a model *Megalosaurus* (below) in the 1850s, before any complete dinosaur skeletons had been found. With so little evidence Owen made a good guess, but the model is largely wrong. The same sculptor made the *Iguanodon* model opposite.

CONTROVERSIAL MODELS
This model of *Megalosaurus*, based on fossils described by Buckland, was later made into a life-size dinosaur and put on show at the Crystal Palace in London alongside others. When the city fathers of New York commissioned a similar exhibition for Central Park, a local judge attacked the models as "antireligious," and the plan ended when someone broke into the workshop and destroyed all the models.

Jaw fragments found by Buckland

Fragments fitted into outline of skull



DARWIN'S ENEMY
Richard Owen (1804–1892), who coined the word "dinosaur," also wrote a scathing review of Darwin's *The Origin of Species* and predicted that Darwin would be forgotten in 10 years' time. In later life, Owen resented Darwin's fame and implied that he had developed an evolutionary theory of his own long before Darwin. Owen was present when, on New Year's Eve, 1853, 21 scientists ate dinner inside his model of the *Iguanodon* (below) before it joined other dinosaur models at London's Crystal Palace.

GIDEON MANTELL
On the basis of the bones and teeth that he had found, Mantell imagined *Iguanodon* to be like a large lizard. In his reconstruction Mantell placed the hornlike spike (below) on the tip of the animal's nose. It was later discovered to be a thumb spike.

DOZENS OF DINOSAURS
In 1878 coal miners in Belgium found 39 *Iguanodon* skeletons. Fossil footprints suggested that *Iguanodon* might have walked on its hind legs. It was believed to have stood semi-upright, so the skeletons of an emu and a wallaby were studied for this Belgian reconstruction.

Cast of *Iguanodon* "horn"

Misplaced thumb spike

CHANGING IDEAS
This modern view of *Iguanodon* is based on detailed studies of marks on the bones, which can reveal much about muscles and tendons. They show that it walked mainly on two legs, with its horizontal body balanced by a rigid tail.

SECRET AUTHOR
In 1844, as dinosaur discoveries amazed the public, a pro-evolution book called *The Vestiges of Creation* was published. Robert Chambers (1802–1871) was revealed as its author only after his death. Chambers tried to make evolution respectable but was heavily criticized by scientists for inaccuracies. Even so, it was very popular and warned Darwin of potential problems.

SCALING UP
This model *Iguanodon* and other models were later scaled up to make the giant reptiles displayed at the Crystal Palace since 1854.

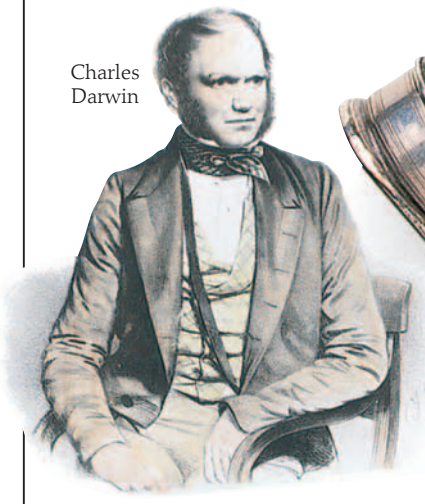
Charles Darwin

CHARLES DARWIN (1809–1882), THE ENGLISH NATURALIST, is well known as the author of *The Origin of Species*. He was not the first to think of evolution, and his real achievement was to present a coherent argument for evolution backed up by a mass of accurate information. In the early 19th century the concept of evolution was very unpopular. Lamarck's theory (p. 12) had been taken up in revolutionary France in the 1790s because it challenged the authority of the church and the king. The fear of a similar revolution in England made evolution a scandalous idea. In fact, the zoologist Professor Robert Grant lost his position at the University of London and died in poverty because he openly supported Lamarck's views. When an anonymous book on evolution, *The Vestiges of Creation* (p. 19), was published in 1844, it met with outrage. All this encouraged Darwin to keep quiet for as long as possible. "It is like confessing a murder," he wrote to a friend as his theory steadily took shape in his mind. In 1858, when the naturalist Alfred Wallace also hit upon the idea of natural selection (p. 36), Darwin was finally forced to publish.

Telescope used on the *Beagle*

Darwin's compass

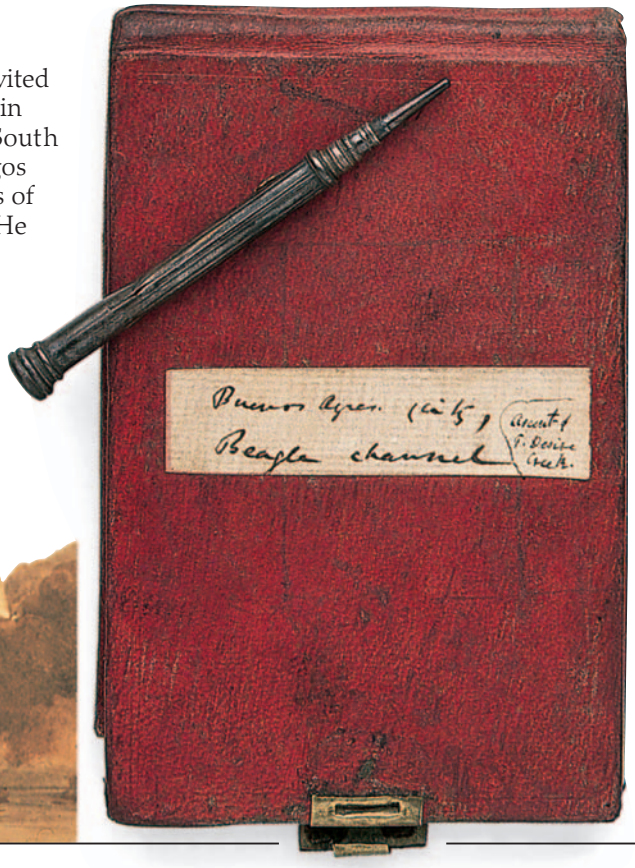
TAKING NOTES
While living aboard the *Beagle*, Darwin took up the habit of making careful observations of the natural world. He also made long and detailed notes, recording everything that he saw, and he thought hard about the meaning of his scientific observations.



Charles Darwin

HMS *Beagle*

From 1832 to 1836 Darwin was invited on the *Beagle*'s world voyage by Captain Fitzroy as companion and naturalist. In South America, and particularly in the Galapagos Islands, he noted many puzzling features of the plants and animals that lived there. He later understood that these peculiarities were the results of evolution.



One of Darwin's notebooks

THINKING AFLOAT
Darwin was not an evolutionist when he stepped aboard HMS *Beagle*, nor when he returned. But over the next five years the idea took shape in his mind. He was never dogmatic about his theory but considered all his opponents' views carefully. In later years this approach helped Darwin to gain support from some of the leading naturalists of his day—even those who had previously rejected evolution.

GOING ASHORE
On the voyage, Darwin took with him a copy of Charles Lyell's new book *Principles of Geology* in which Lyell claimed that the geological features of Earth could be explained by slow-acting forces that were still at work, such as the laying down of sediment. Darwin spent much time ashore, and his observations of geology confirmed Lyell's theory, implying that Earth was very old.

People of Tierra del Fuego greet the *Beagle*

A great naturalist

Before the *Beagle* voyage, Darwin studied to be a clergyman at Cambridge University. While there, he developed a passionate interest in natural history—an interest that was to change the course of his life.

Erasmus Darwin

ERASMUS DARWIN
Charles's grandfather, Erasmus Darwin (1731–1802), was a doctor, poet, and botanist. He was also a friend of scientists and industrialists, such as Joseph Priestley and Josiah Wedgwood, who questioned conventional ideas and were considered dangerous. Even before Lamarck (p. 12) he wrote a long epic poem about evolution. The next generation of the Darwin family, anxious to seem more respectable, largely ignored Erasmus's books.

Scissors used in dissection

Ivory handle

Magnifying glass

Mounted needle used in dissection

Lens

Butterfly wing

Collecting boxes, beetle, and microscope slide from Down House

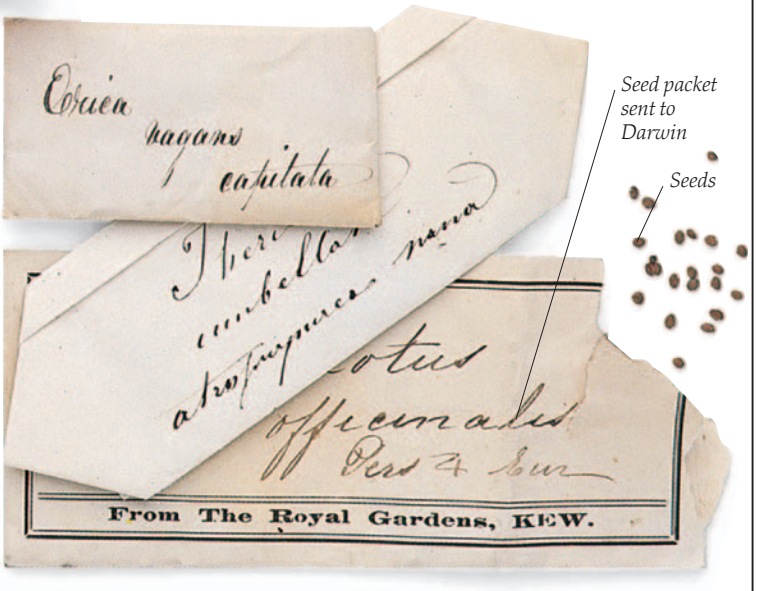
COLLECTING DATA
Darwin grew many plants in the greenhouses at his home, Down House. He was particularly interested in climbing and twining plants, insect-eating plants, and orchids. He dissected the flowers of orchids and made some amazing discoveries about how these flowers are pollinated. Other naturalists sent him seeds or whole plants that might interest him, and some of the seed packets have survived to this day (right). Darwin's work would have made him famous as a great biologist even if he had never written *The Origin of Species*.

Part of Darwin's beetle collection

BEETLE MANIA
During his student days at Cambridge, Darwin was an enthusiastic collector of beetles. This is part of his enormous collection. Being an experienced practical naturalist was a great strength for Darwin. When it came to discussing plants and animals, he had firsthand knowledge of the subject.

ALL ABOUT WORMS
After writing *The Origin of Species*, Darwin continued his work as a naturalist. He felt that looking at the small details of living things was just as important as devising grand theories. One of his later books was devoted entirely to earthworms, which clearly puzzled this cartoonist.

A cartoon from the humorous magazine *Punch*



Seed packet sent to Darwin

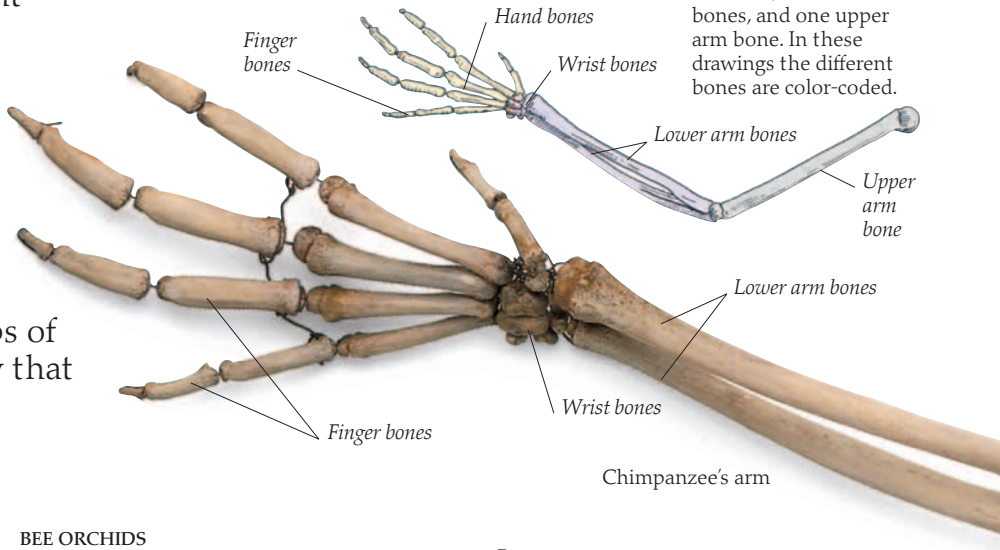
Seeds

Living evidence

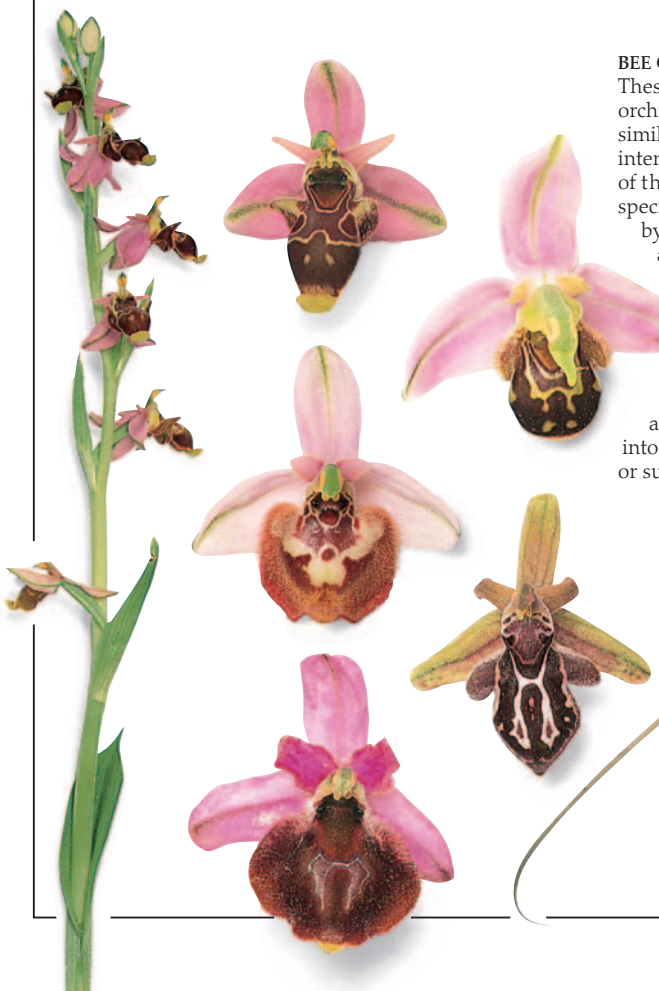
THINKING THE SAME WAY
Constantine Rafinesque was an eccentric American naturalist who saw the signs of evolution.

DARWIN SET HIMSELF two major tasks. One was to work out a mechanism by which evolution might occur. The mechanism he thought of was natural selection (p. 36), which is still accepted today as the main force behind evolution. His other task was to collect enough evidence to convince people that evolution had occurred. Some evidence came from fossils (p. 26) or from plant and animal distribution (p. 24). Most important was the evidence from living things. This was clear enough to have been noticed by other naturalists, including Rafinesque, who wrote in 1836, "All species might have been varieties once, and many varieties are gradually becoming species." Such casual remarks by naturalists carried little weight, but Darwin was more difficult to ignore because he produced so much data. One important piece of evidence was that the same basic pattern of bones appears in the limbs of all mammals. Such similarities show that they must all be descended from a common ancestor.

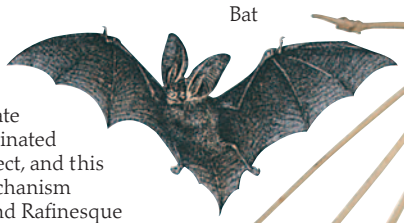
CHIMPANZEE'S ARM
The arm and hand of the chimpanzee are close to the basic vertebrate pattern, having five fingers, five hand bones, a set of small bones in the wrist, two lower arm bones, and one upper arm bone. In these drawings the different bones are color-coded.



Chimpanzee's arm



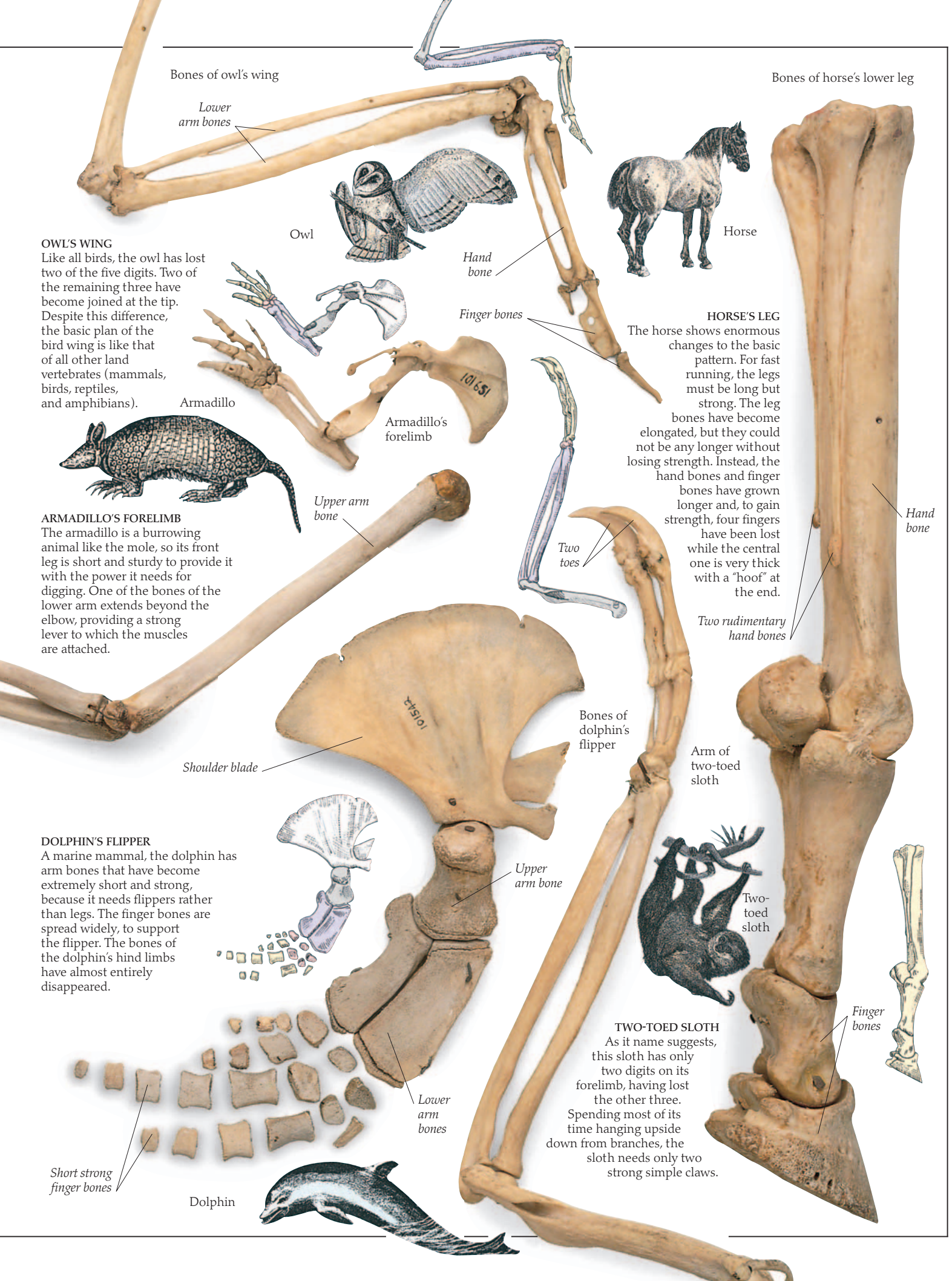
BEE ORCHIDS
These Mediterranean bee orchids look remarkably similar, but they cannot interbreed. Therefore, each of them belongs to a separate species. Each species is pollinated by a different type of insect, and this acts as an isolating mechanism (p. 41). Darwin and Rafinesque were both struck by groups of very similar species such as these. It seemed obvious that they must have evolved from a single ancestral species. This ancestor probably developed into a number of varieties or subspecies (p. 13) first.



Bat

Bones of bat's wing

BAT'S WING
In bats, the hand and finger bones have developed into supports for the membranes of the wing. The similarity in basic structure between a bat's wing and a dolphin's flipper is strong evidence for evolution.



OWL'S WING
Like all birds, the owl has lost two of the five digits. Two of the remaining three have become joined at the tip. Despite this difference, the basic plan of the bird wing is like that of all other land vertebrates (mammals, birds, reptiles, and amphibians).

ARMADILLO'S FORELIMB
The armadillo is a burrowing animal like the mole, so its front leg is short and sturdy to provide it with the power it needs for digging. One of the bones of the lower arm extends beyond the elbow, providing a strong lever to which the muscles are attached.

DOLPHIN'S FLIPPER
A marine mammal, the dolphin has arm bones that have become extremely short and strong, because it needs flippers rather than legs. The finger bones are spread widely, to support the flipper. The bones of the dolphin's hind limbs have almost entirely disappeared.

HORSE'S LEG
The horse shows enormous changes to the basic pattern. For fast running, the legs must be long but strong. The leg bones have become elongated, but they could not be any longer without losing strength. Instead, the hand bones and finger bones have grown longer and, to gain strength, four fingers have been lost while the central one is very thick with a "hoof" at the end.

TWO-TOED SLOTH
As it name suggests, this sloth has only two digits on its forelimb, having lost the other three. Spending most of its time hanging upside down from branches, the sloth needs only two strong simple claws.

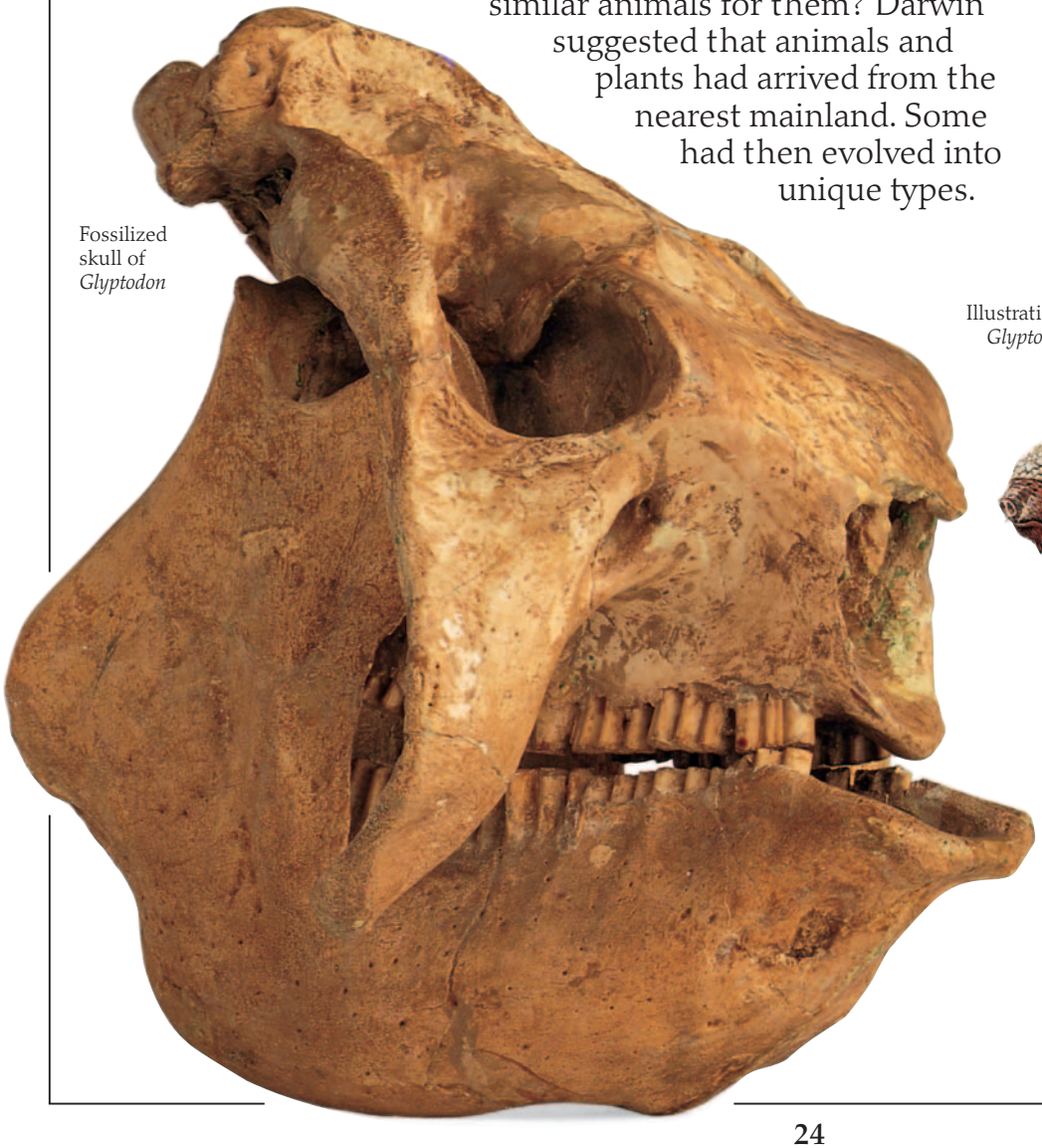
Animal and plant distribution

PLANT HUNTER
The botanist Joseph Hooker (1817–1911) searched for new plants in the Himalayas and New Zealand and was director of the Royal Botanic Gardens at Kew, near London. Darwin's good friend and colleague, he told him a great deal about plant distribution.

In Darwin's time, it was believed that each species had been created by God to suit best the conditions of a particular place. This "special creation" theory had many weak points, as Darwin made clear. In Australia mammals introduced from Europe had overrun the country, wiping out some native mammals. If Australian animals were exactly right for Australia, how could this happen? Darwin showed how migration and evolution could explain the patterns of distribution far better. Islands were an important part of his argument. The animals of the Cape Verde Islands are basically like those in Africa, and the Galapagos animals are like South American animals. Since these two island groups have much the same conditions, why had the Creator not made similar animals for them? Darwin suggested that animals and plants had arrived from the nearest mainland. Some had then evolved into unique types.

Thick bony plate from the outer covering of a Glyptodon

ARMORED ANCESTOR
While in South America, Darwin found the remains of a *Glyptodon*, a prehistoric giant armored mammal. He realized that it resembled the living armadillos of South America. This continuity between animals of the past and present had also been found in Australia, and it provided strong supporting evidence for the idea of evolution.



Fossilized skull of *Glyptodon*

Illustration of *Glyptodon*

ONCE ON AN ISLAND
The modern armadillo is just one of the many unusual mammals of South America. If animals and plants could travel freely, there should be roughly the same species everywhere, but, in fact, there are many blocks to migration, such as oceans, deserts, and mountain ranges. South America was an island for millions of years, and many unique mammals evolved there during this time.

Modern armadillo

New Zealand

The animals on these islands are well explained by evolution. Strong sea currents prevented most mammals from getting there, so birds and insects, which arrived by air, evolved to fill some of the slots normally taken by mammal species.

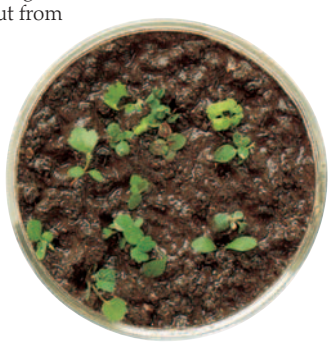
MOAS AND KIWIS
The flightless kiwi is found only in New Zealand, as were the giant flightless birds called moas, which are now extinct. Moas and kiwis evolved from flying birds that colonized the islands of New Zealand millions of years ago.


Kiwi


Giant moa

GHOSTLY FOOT
The moas died out very recently because of overhunting. Their undecayed remains (not fossils) are still sometimes found in caves. This is a foot from this enormous bird.

Seedlings sprout from mud



WANDERING PLANTS
How could plants travel to an island? This question was crucial for Darwin. He imagined that waterbirds, which fly long distances and rest on islands, might unintentionally transport plant seeds. He scraped dry mud from birds' feet and mixed it with water—seedlings sprang up, as he had expected.

GIANT CRICKET
Because there are no mice in New Zealand, the giant bush cricket, or weta, has evolved to fill the slot that mice occupy elsewhere. In general, mammals are less able to cross oceans than are birds, reptiles or insects.

Weta, life size

The Galapagos

His visit to the Galapagos islands provided Darwin with some excellent evidence. In general, the animals of the islands resembled those of South America, but many species were unique to the Galapagos.

Map of Galapagos Islands from *A Naturalist's Voyage Round the World* by Darwin

CHANCE LANDING
The Galapagos Islands are some 800 miles (1,300 km) from South America. All the Galapagos finches are probably descended from a small mainland flock that was blown off course and reached the islands millions of years ago.

Galapagos finches

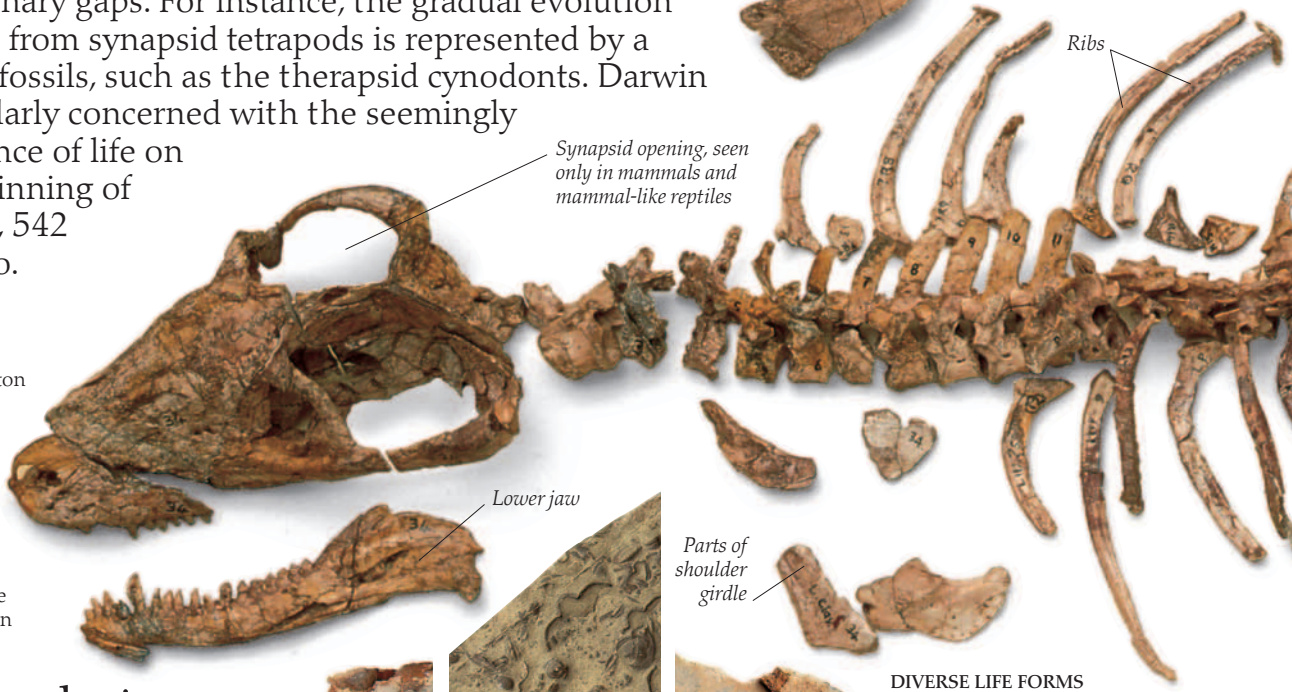
DARWIN'S FINCHES
The Galapagos finches are clearly related to a type of finch from South America. Each of the 13 species has a differently shaped beak. The beaks are adapted to different kinds of food ranging from insects to seeds.

ATTACKED BY BIRDS
Henry Bates (1825–1892) helped Darwin by supplying him with data on animals and plants in the Amazon rain forest. Bates was one of many naturalists to study distant parts of the world for the first time, and Darwin sought information from several of them.

Fossil evidence

INSIDE STORY
Sliced in half, an ammonite reveals its intricate chambers.

DARWIN STUDIED the fossil record carefully for evidence that evolution had occurred. At the time fossils did not provide him with the evidence that he needed. He hoped that fossils would bridge the evolutionary gaps between the major groups of living animals but these were not immediately forthcoming. Darwin explained their absence by arguing that the rock record was far from complete. He was also aware that many paleontologists would use their expertise to criticize his evolutionary theory and so did not try to use fossils to support his theory. Today, we know that while the rock record does, in fact, have many gaps, there is now plenty of fossil evidence that fills the evolutionary gaps. For instance, the gradual evolution of the mammals from synapsid tetrapods is represented by a series of extinct fossils, such as the therapsid cynodonts. Darwin was also particularly concerned with the seemingly sudden appearance of life on Earth at the beginning of Cambrian times, 542 million years ago.

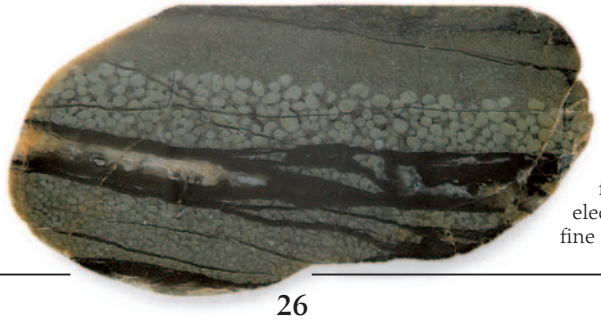


ALMOST A MAMMAL
This is the fossilized skeleton of an animal called *Procynosuchus*, a type of extinct synapsid tetrapod (a reptile with mammalian features) known as a cynodont. It was from the cynodonts that the true mammals evolved, so they have more mammalian characters than their predecessors.

Cambrian explosion

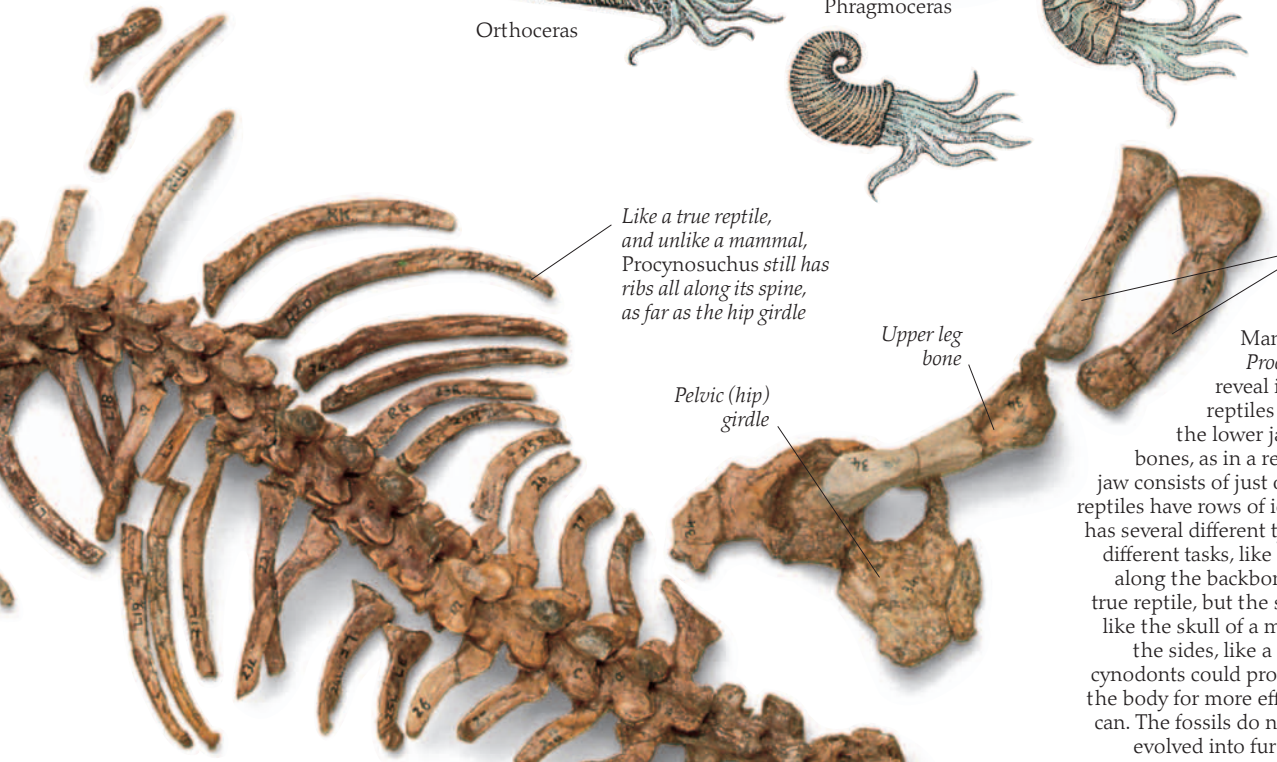
Darwin's answer to the problem of the sudden appearance of life in the Cambrian, the "Cambrian explosion," was to predict that, as more Precambrian rocks were explored, fossils would be found. This has indeed happened, and now the fossil record extends back to over 3 billion years ago, but until late Precambrian times the remains are of very primitive organisms. Even then, larger fossils, such as the soft-bodied Ediacaran fossils (p. 47), thought to be multicellular organisms, cannot yet be linked to the common early Cambrian invertebrates such as trilobites and brachiopods.

DIVERSE LIFE FORMS
These pieces of rock (left) are all from the Cambrian period, and they contain the remains of very different kinds of animals with shells—marine mollusks (far left), several kinds of trilobite, (center), and an animal called *Ridersia*. Their appearance in the fossil record is very sudden, and their immediate ancestors remain something of a mystery.



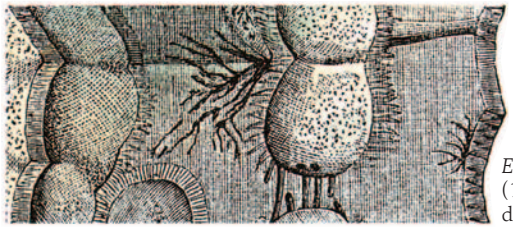
ANCIENT CELLS
The circles on this Precambrian rock are fossil colonies of cyanobacteria, or blue-green algae. To check that these were living things, scientists can now use chemical analysis of the rock, a technique unavailable for *Eozoon* (see right). With a scanning electron microscope, even the detail of their fine structure can now be seen.

COILED SHELLS
These fossil cephalopods are not a sequence of ancestors and descendants, but they give an idea of the evolutionary steps that led to the tightly coiled shells of the marine animals called ammonites (far right). The earliest stage developed a shell divided into chambers, most of which were air-filled and acted as a float. This float proved useful, but as larger species evolved, a long buoyant shell must have been hard to steer when swimming. Coiling offered a solution to this problem.

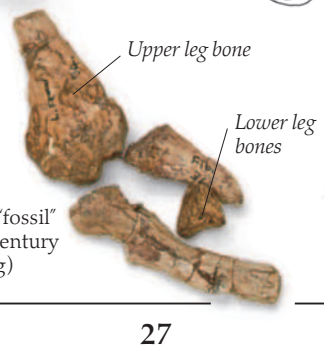


HALFWAY IN BETWEEN
Many features of the skeleton of *Procynosuchus*, illustrated below, reveal its halfway position between reptiles and mammals. For example, the lower jaw is still made up of several bones, as in a reptile, while in mammals the jaw consists of just one bone. However, whereas reptiles have rows of identical teeth, *Procynosuchus* has several different types of teeth, specialized for different tasks, like a mammal. There are ribs all along the backbone as far the hip girdle, like a true reptile, but the skull has a synapsid opening like the skull of a mammal. The legs stick out at the sides, like a lizard's, but in an emergency cynodonts could probably pull them underneath the body for more efficient running, as crocodiles can. The fossils do not tell us whether scales had evolved into fur yet, but scientists think that *Procynosuchus* may have had fur.

FALSE FOSSILS
When "fossils" were first found in Precambrian rocks in Canada, Darwin was delighted. They were given the name of *Eozoon* ("dawn animal"), but they turned out to be nothing more than mineral crystals.



Eozoon "fossil" (19th-century drawing)



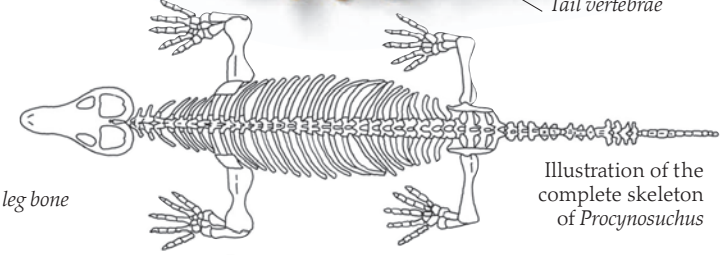


Illustration of the complete skeleton of *Procynosuchus*

Artist's impression of *Procynosuchus*

How old is Earth?

SLOW FORCES
The geological theories of Charles Lyell (1797–1875) were a reaction against Cuvier's catastrophe theories (p. 16). Lyell set out to explain geology using only natural forces that were still at work, rather than relying on ancient catastrophic floods as Cuvier did. Since present-day forces work very slowly, Earth must be very old, Lyell claimed.

HAVING LOOKED AT THE EVIDENCE of living things (pp. 22 and 24) and of fossils (p. 26) , Darwin became convinced that evolution had occurred. At the same time, he asked himself *how* it might have occurred. In 1838 he hit on his theory of natural selection (p. 36). An obvious feature of natural selection is that it could not work quickly, because it is haphazard rather than purposeful. Darwin knew that evolution through natural selection needed an enormous amount of time, but this did not worry him, as Charles Lyell's *Principles of Geology* had convinced him that Earth was many hundreds of millions of years old. Since Lyell's time, geological research has confirmed his basic ideas, and he is known as the "father of modern geology." In 1866, however, the physicist William Thomson launched an attack on both Lyell and Darwin, claiming that Earth was, at the most, 100 million years old. Later, his figure fell to 20 million years. His calculations were based on the rate of heat loss from Earth, the present temperature of the outer crust, and the assumption that it had originally been molten. Darwin called this "one of my sorest troubles," and in later editions of *The Origin of Species* he played down natural selection, emphasizing other supposed mechanisms that he thought would work faster. Not until 1904 did Thomson's fundamental error become clear.

Geological map of the Weald from the 19th century

Cross-section through the Weald

THE AGE OF THE WEALD
Darwin's interest in Earth's age and how it might be estimated led to some experiments and calculations of his own. The area of southern England where he lived, called the Weald, consists of layers of sediment that were laid down under the sea, later forced upward into folds, and then eroded away. Darwin tried to work out the age of the Weald by estimating its original height and the rate of erosion. The rate was too slow, and his date of 300 million years was wildly wrong. The Wealden hills are only 20–30 million years old.

Worm stone set up at Down House, Darwin's home

THE WORM STONE
Darwin's interest in time and how it changed Earth took a new turn with his studies of earthworms (p. 21). He suspected that the action of worms in the soil would slowly bury buildings. To measure the speed of this, he placed a heavy millstone on his lawn, and this special instrument (right) was made to measure how far the stone sank each year.

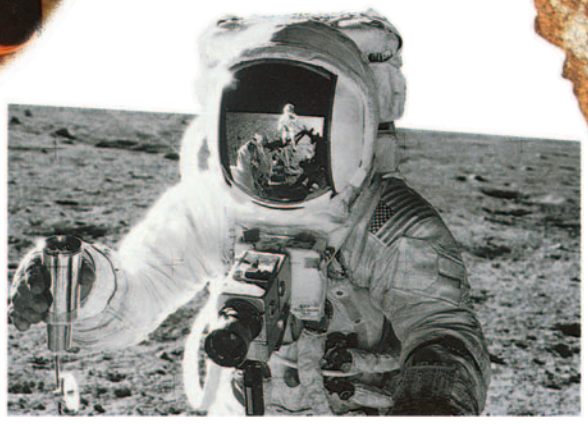
WRONG ANSWER
Radioactive emissions were discovered in 1896, and in 1903 Pierre Curie found that radium salts constantly give out heat, warming Earth's crust. Thomson was unaware of this, and it made his calculation of Earth's age entirely wrong. However, he made the arrogant claim that physics was a superior science to geology or biology. He thought that his one calculation could therefore overrule all the evidence collected by Lyell and by Darwin.

LORD KELVIN
William Thomson (1824–1907) was a British physicist who later became Lord Kelvin. He and his followers had some religious motives for attacking Darwin. Like many other people, they disliked the fact that natural selection showed no purpose or direction.

ASTRONOMER SON
George Darwin (1845–1913), one of Charles's 10 children, was a mathematician and astronomer. Asked by his father to check Thomson's calculations about the age of Earth, he concluded that they were mathematically correct. In later life, George Darwin was among the first to recognize that radioactivity was constantly warming Earth's crust, making Thomson's calculations meaningless.

RADIOMETRIC DATING
Radioactive elements in rocks now allow them to be dated accurately. Each radioactive element breaks down at a constant rate and always forms the same product. For example, potassium 40, found in volcanic rocks, breaks down to give argon 40. The older the rock, the more argon 40 there is. Earth's original rocks have mostly been recycled by geological processes but by measuring the age of the oldest minerals (4.4 billion years) compared with the age of meteorites (4.5 billion years), geologists have calculated Earth's age as 4.5 billion years.

DATES CONFIRMED
Meteorites were formed at the same time as Earth. Radiometric dating shows that they are 4.5 billion years old. The ages of Moon rock and meteorites have both confirmed the age of Earth that was calculated by modern geologists.



MOON ROCK
Rock samples brought back from the Moon have proved useful to geologists. The Moon and Earth were formed at the same time but, since there is no atmosphere on the Moon, there is no erosion. As predicted, geologists' calculations make Moon rock 4.5 billion years old.

IMPOSSIBLE PLANT
No one has managed yet to breed a cabbage that will grow to the size of a tree.

Artificial selection

As part of his search for evidence about evolution, Darwin looked at domesticated animals and plants. During his lifetime, great progress had been made in developing new varieties of plants and animals through "artificial selection" or "selective breeding." This involves choosing those individuals that have the desired qualities and breeding only from them, rejecting the rest. Knowing the extent to which certain species of plants and animals had been improved in the preceding 50 years, Darwin argued that far greater changes were possible over thousands of years. This made him suspect that all breeds of sheep, for example, were descended from a single ancestor. Other naturalists disagreed—they thought that every breed must have come from a different wild species. One naturalist even suggested that there had once been *eleven* different species of wild sheep in Britain, found nowhere else in the world. Darwin pointed out how unlikely this was, since all Britain's living mammals are also found in Europe. Subsequent evidence has shown that Darwin was correct: all the different breeds of sheep were indeed developed by selective breeding from just one ancestor. The same is true of other domesticated animals, such as cows, dogs, and horses.

ROCK DOVE
This wild bird is the raw material with which pigeon breeders began. All the different pigeon breeds kept in captivity are descended from it.

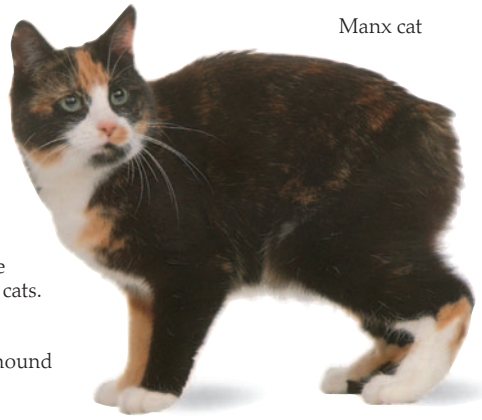
DARWIN'S HOBBY
In addition to his horse, Darwin kept rabbits, chickens, ducks, and pigeons. He crossed all the different breeds of pigeon and was surprised that the young often had the same colors as the rock dove, even if neither parent had them. He realized that the rock dove must be the ancestor of them all.

PIGEON BREEDS
These are some of the many different breeds of pigeon that Darwin studied. He felt that if so much change could come about through selective breeding, then similar changes could occur through the action of natural forces alone.

ANCIENT CATTLE
Wall paintings in the tombs of ancient Egypt show cattle of many different breeds. Some naturalists saw such paintings as evidence that every breed was descended from a different species. After all, these breeds already existed thousands of years ago. Darwin argued that there was no reason to assume that the Egyptians were the first farmers—selective breeding could have begun even earlier. There is now ample evidence that his idea was correct.

GIANT DOG
The Irish wolfhound is one of the largest dogs: it can be 40 in (1 m) tall at the shoulder. The smallest, the chihuahua, may stand only 8 in (20 cm) tall. Studies of their DNA (p. 52) show that all breeds of dog are descended from the European wolf.

TAIL-FREE CAT
The Manx cat has been bred to have no tail. Cats are more difficult to breed selectively than dogs, since they like to roam at night and mate as they please. Many dog breeds were developed for useful purposes, which explains why they are more varied than cats.



Manx cat

Irish wolfhound

Cherry tomatoes

BIG, BIGGER
Plant breeders can easily produce smaller or larger breeds, as these tomatoes show. The ancestral plant has been found in South America, and its tiny "tomato" is no larger than a redcurrant.

Giant tomato

BALD DOG
The Chinese crested dog is virtually naked except for long wisps of hair on its head and tail. Breeders can alter the temperament, size, shape, and color of a dog. Its coat can be made long or short, straight or curly.

Chinese crested dog

STRANGE FRUIT
Yellow tomatoes and red grapefruit are just two of the oddly colored fruits created by plant breeders. Darwin was convinced that artificial selection indicated a way in which evolution could occur—through a process that he called natural selection (p. 36).

Yellow tomato

SEEDLESS PRODUCE
In nature, fruits exist solely to distribute seeds. If there are no seeds inside it, a young fruit will normally wither and die. Breeders have managed to overcome this so that certain fruits, including bananas, some grapes, and some oranges, have no seeds.

Pink grapefruit

Seedless orange

All cultivated bananas are seedless

Seedless grapes

Variation and inheritance

By 1837 Charles Darwin was certain that evolution had taken place, and he was thinking hard about the driving force behind it. For a while, he thought that Lamarck's theory about striving for change (p. 12) was the answer, but Darwin soon saw its weak points. He began taking an interest in anything that might answer this difficult question, including the breeding of crop plants, farm animals, and pets (p. 30). By questioning breeders, he learned that there were small variations between individuals, which the breeders picked out. A dog breeder would choose a feature and cross two dogs carrying it. From the puppies, those that had inherited the chosen feature would be picked out and bred. If this was repeated for several generations, the feature became more and more pronounced. Darwin saw that a similar process could occur in the wild, and he called it "natural selection" (p. 36). The three ingredients needed were variation, inheritance, and competition. Inheritance clearly took place, although Darwin never really understood how. Variation between individuals was also apparent. The third factor, competition, or "the struggle for existence," was also a fact of nature (p. 34). Competition in the wild had the same role as the dog breeder, "selecting" particular individuals for breeding and discarding others.

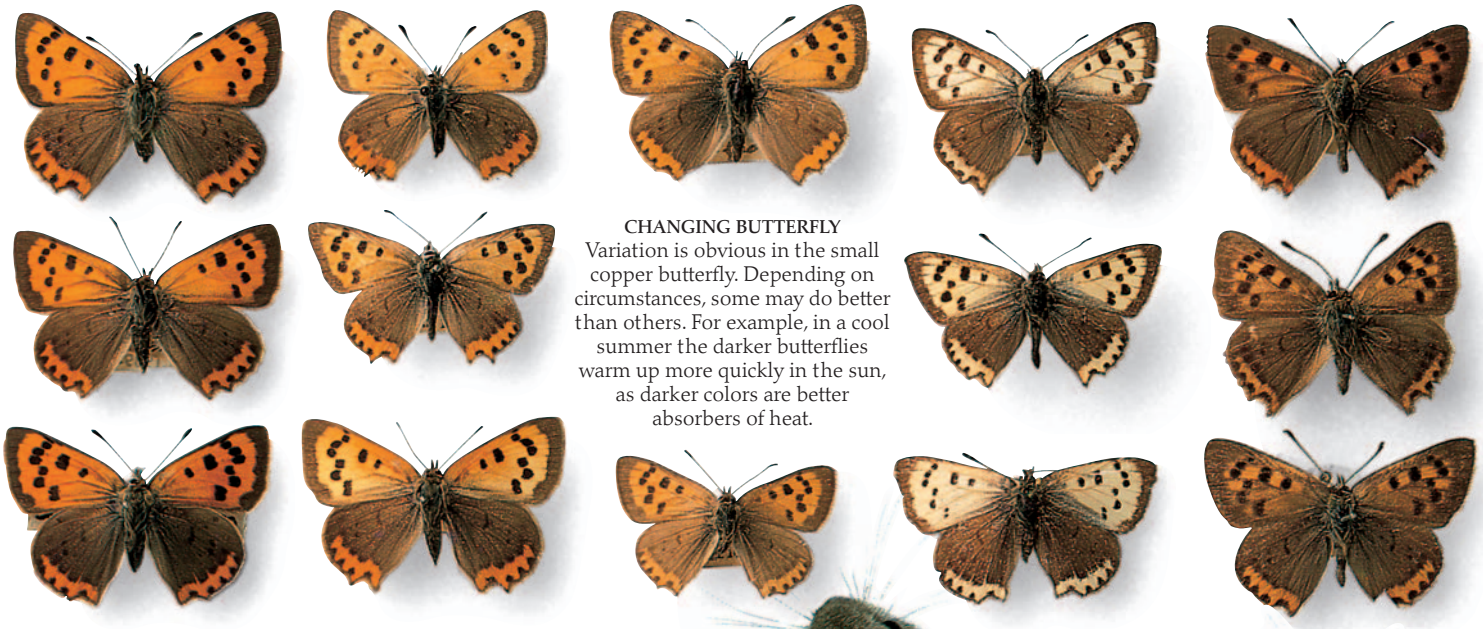
NO TWO THE SAME
Variation is shown in the shell colors and patterns of a seashore mollusk, *Nerites*. Not all variation is as obvious as this. There may be very small variations in size or shell thickness that are not noticeable, but that affect the animal's survival. Studies of internal features show even more differences between individuals.

Varied *Nerites* shells

Normal teasel

Fuller's teasel

MUTANT TEASEL
Fuller's teasel is a mutant form of the teasel plant that has curved spines on the seed-head instead of straight ones. Mutants were observed in the 19th century, but only in the 20th century were they studied systematically by geneticists (p. 51). Mutants arise through a sudden change, or mutation, in the DNA. This change occurs because the DNA is copied inaccurately when the reproductive cells are being produced (p. 53). Mutations are not dictated by the needs of the plant or animal. In fact, most mutations are damaging, and the mutants die young. But a few mutations are useful, and these are a major source of the variation on which natural selection operates.



CHANGING BUTTERFLY
Variation is obvious in the small copper butterfly. Depending on circumstances, some may do better than others. For example, in a cool summer the darker butterflies warm up more quickly in the sun, as darker colors are better absorbers of heat.

Darwin and heredity

Darwin's greatest problem was heredity. He believed, wrongly, that acquired characteristics (p. 13) are inherited. But, unlike Lamarck, Darwin did not make this the cornerstone of his theory. He thought that random variation and selection were more important. Darwin's more significant mistake was to think that the characteristics of the parents would blend in the offspring. He could see that if inheritance did involve the blending of characteristics, this would be an obstacle to evolution by natural selection, because if one parent had a useful new characteristic it would be diluted in the offspring. Despite this, he could think of no alternative.

FAMILY TRAITS
Inheritance is obvious in most families. However, children often do not look like their parents; rather, they resemble their grandparents or other relatives. Darwin was puzzled by this, but geneticists later realized that "dominant" and "recessive" genes (p. 51) were responsible.

Normal young

Albino young

COLOR CLUE
Darwin knew that when albino and normal mice are crossed, the colors do not blend in the young. He found several other examples, but thought they were just oddities, exceptions to the rule. In fact, they held the key to heredity, as Mendel showed (p. 51).

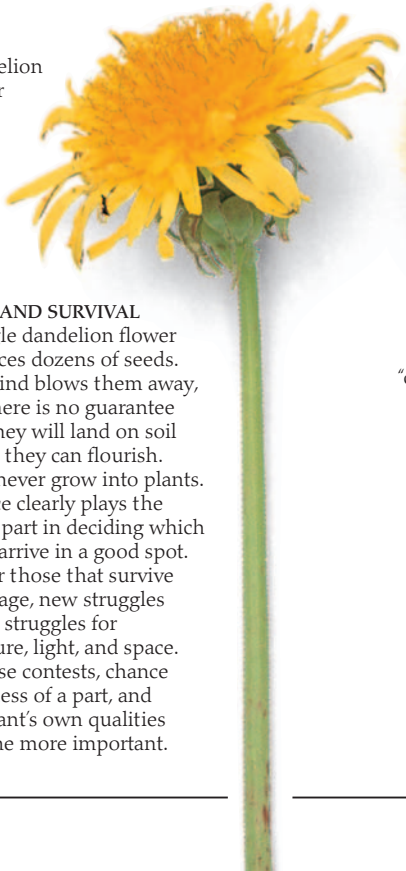
Normal father Dwarf Russian hamster

Albino mother Dwarf Russian hamster

The struggle for existence

MANY ANIMALS lay hundreds of eggs every year. Very few of these live to become adults—a fact that is obvious to any naturalist. The poet Alfred Lord Tennyson was aware of this when, in 1833, he wrote "Are God and Nature then at strife, That Nature lends such evil dreams? So careful of the type she seems, So careless of the single life." Unlike Tennyson, most people preferred to ignore the facts and see nature as happy and harmonious, a view made popular by the Reverend William Paley (p. 38). Darwin knew that plants and animals died in great numbers, but it took years for him to realize that this loss of life could be the driving force behind evolution. A naturalist and clergyman, the Reverend Thomas Malthus, helped him see the light. In 1798 Malthus had published *An Essay on the Principle of Population*, which argued that all living things tend to increase far faster than food supplies and that, in the case of humans, numbers are only kept in check by famine and disease. These ideas were well known to Darwin, but he did not actually read Malthus's essay until 1838. As soon as he read it, the idea of natural selection (p. 36) came to him in a flash, enabling him to make sense of all his earlier observations. Nevertheless, Darwin was always troubled by the "wasteful works of Nature." He consoled himself with the thought that "the war of nature is not incessant, that no fear is felt, that death is generally prompt, and that the vigorous, the healthy, and the happy survive and multiply."

STARVING THE POOR
The Reverend Thomas Malthus (1766–1834) was a kind man, but his essay inspired a brutal new Poor Law in Britain. The law took welfare support away from the poor unless they went into prisonlike "workhouses" where husbands and wives were separated. Feeding poor people, according to Malthus, only made poverty worse in the long run, because the poor then had more children.



Dandelion flower

LUCK AND SURVIVAL
A single dandelion flower produces dozens of seeds. The wind blows them away, and there is no guarantee that they will land on soil where they can flourish. Most never grow into plants. Chance clearly plays the major part in deciding which seeds arrive in a good spot. But for those that survive this stage, new struggles begin: struggles for moisture, light, and space. In these contests, chance plays less of a part, and the plant's own qualities become more important.

Tufted seeds

Dandelion "clock" with dry seeds ready to disperse

Dandelion head after the seeds have been blown away

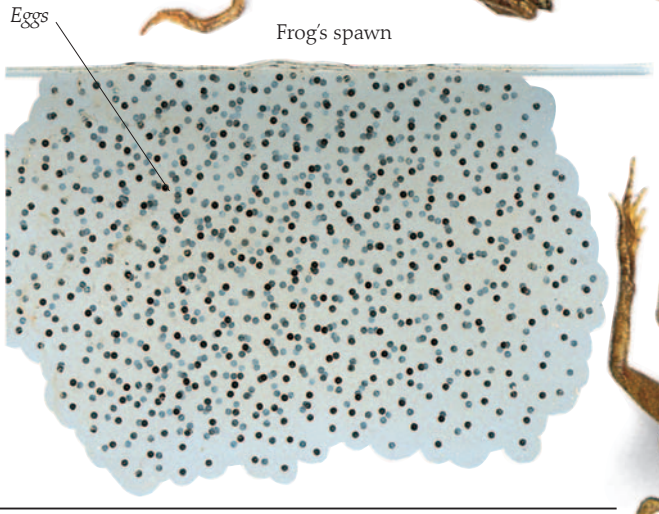
Dozens of seeds from a single head

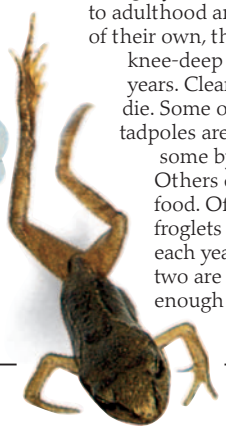
FIGHTING FOR SPACE
Like most seabirds, gannets are vulnerable to predators when nesting, so they nest only on small, rocky islands where there are no rats or foxes to destroy their eggs and young. As suitable islands are few, they become very crowded. Competition between animals for nesting sites is another aspect of the "struggle for existence."

HUNTER AND PREY
A thin and hungry polar bear pursues a nimble arctic fox across the snow. One of the most important parts of the struggle for survival is the need to eat—and the need to keep from being eaten by others.

Froglets set off into the wide world

RED IN TOOTH AND CLAW
The poet Alfred Lord Tennyson wrote his poem *In Memoriam* in 1833, 25 years before Darwin published *The Origin of Species*. It includes the memorable line "Nature red in tooth and claw." This phrase later came to symbolize people's hatred for the idea of natural selection. They reacted as if Darwin had invented the struggle for existence, rather than simply described it.





THE NUMBERS GAME
A frog can lay hundreds of eggs in a single year. If all these survived to adulthood and produced young of their own, the world would be knee-deep in frogs within 10 years. Clearly, most of them die. Some of the eggs and tadpoles are killed by fungi, some by predators. Others die from lack of food. Of the few dozen froglets that may survive each year, only one or two are likely to live long enough to breed.

Adult frog

Natural selection

GREAT MINDS
In 1858 British naturalist Alfred Wallace (1823–1913) wrote to Darwin from Malaya, asking advice on a short article he had written. To Darwin's dismay it contained the idea of natural selection. Wallace did not know that Darwin had been working on this idea for 20 years. A joint publication was hastily arranged.

How does evolution occur? Charles Darwin's answer was through "natural selection." He realized that there was always some variation between individuals within a species (p. 32), so that some are a little larger, some have thicker fur, or slightly longer legs. He also realized that there is a struggle for existence (p. 34) because more individuals are born than can survive. To some extent, chance plays a part in deciding which ones survive, but the characteristics of the individual must sometimes make a difference. The animal with longer legs will run faster and thus escape a predator. The animal with thicker fur will survive a cold winter. Only those that survive have the chance to produce young ones—and that is where inheritance (p. 33) is important. If the slightly longer legs or thicker fur are passed on to some of the offspring, then more animals have those useful characteristics in the next generation. After hundreds of generations, these small changes may add up to a large and noticeable difference. Darwin proposed that this process produces adaptation (p. 38) and could also produce new species, given enough time (p. 40). The idea of natural selection came to Darwin in 1838, but he spent a further 20 years working on the idea and collecting more evidence. He was nervous about the controversies that his theory might provoke, and this too made him delay publication. Had Alfred Wallace (above left) not reached similar conclusions, Darwin might never have published at all.

WINTER KILLS
Killed by the cold and lack of food, this eagle has lost forever its chance of producing young. Another eagle, with thicker feathers, or better hunting abilities, may survive to produce chicks next spring.

Moths on light bark

Industrial pollution in 19th-century England

Moths on dark bark

CONCEALING COLORS
In the 19th century a good example of natural selection occurred in the industrial regions of northern England, although no one grasped its significance at the time. The peppered moth rests on tree trunks by day. Its pale dappled wings are camouflaged against lichens growing on the trunks, and this protects the moth from insect-eating birds. Pollution kills off lichens, and as industry grew, the tree trunks turned black with soot from factory smokestacks. Dark versions of the peppered moth arose by mutation (p. 32) and were better camouflaged than the original form. Gradually, the dark forms became more and more common.

Sexual selection

Aside from natural selection, Darwin also identified another important mechanism: sexual selection. When animals mate, they are choosy about their partners. Usually it is the female choosing the male, or males fighting to control females. Sometimes, however, females must compete for males, or both partners may be choosy. The qualities that ensure success differ widely, from physical strength to bright feathers. Only those chosen as mates pass on their characteristics to the next generation.

Single tail feather from male peacock

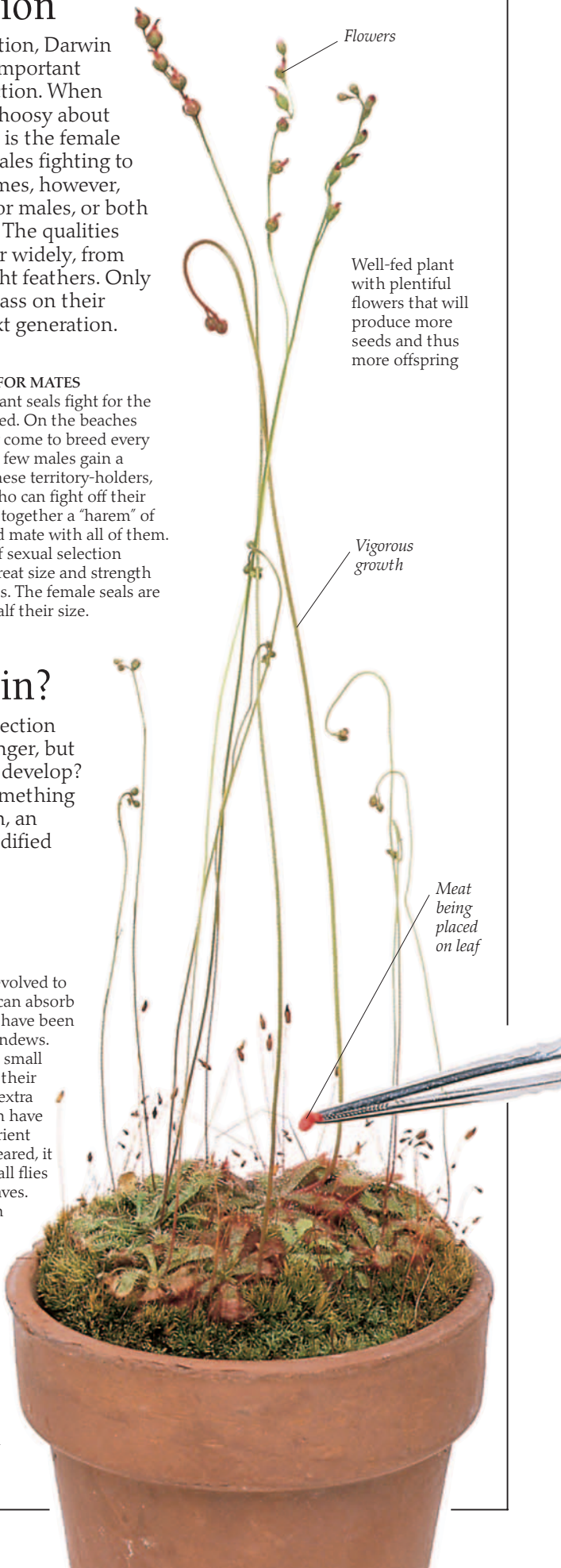
FIGHTING FOR MATES
Male elephant seals fight for the right to breed. On the beaches where they come to breed every year, only a few males gain a territory. These territory-holders, the ones who can fight off their rivals, herd together a "harem" of females and mate with all of them. This type of sexual selection produces great size and strength in the males. The female seals are less than half their size.

APPEALING TAIL
Sexual selection often involves males attracting females. Peacocks display their tails to females, who choose the best-looking male. Bright feathers may originally have been favored because they showed that a male was healthy, but once this process begins, the feathers may become more and more elaborate.

How does it begin?

It is easy to see how natural selection can make fur thicker or legs longer, but how does a totally new feature develop? In every case, there must be something for natural selection to work on, an existing feature that can be modified to make the new one.

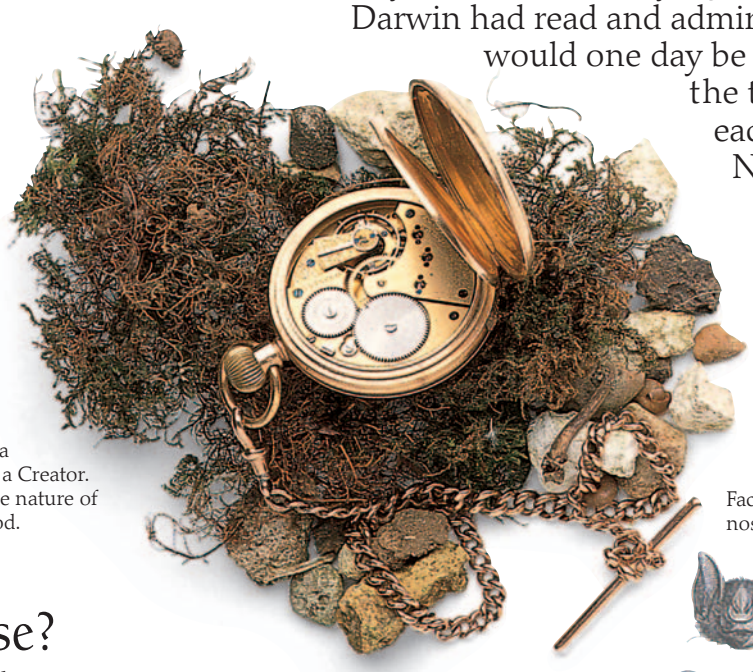
HUNGRY PLANTS
The leaves of the sundew plant have evolved to become insect traps. Most plant leaves can absorb some nutrients directly, and this must have been the starting point for the ancestor of sundews. They grew in bogs with poor soil, and small insects that happened to drown on their damp leaves would have supplied extra minerals. Natural selection would then have favored plants that increased this nutrient supply. If a plant with stickier leaves appeared, it would do better than others, because small flies would become stuck on the leaves. Darwin experimented with sundews, feeding some with small pieces of meat and keeping others unfed. Those fed on meat grew more quickly, produced more flowers, and set more seeds. He had shown that being able to trap and digest insects would be a characteristic favored by natural selection.



Understanding adaptation

William Paley
(1743–1805)

MOLES HAVE STRONG, BROAD FRONT FEET for digging through soil. Ducks have webbed feet for swimming. Polar bears have very thick fur. It is clear to any naturalist that all plants and animals are superbly adapted to their climate and way of life. Darwin proposed that these adaptations were an outcome of natural selection. However, there was already a powerful and popular theory about adaptation known as "natural theology." This interpreted all adaptation as evidence of the creator's handiwork. *Natural Theology, or Evidences of the Existence and Attributes of the Deity,* by the English clergyman William Paley, set out the ideas most fully. Published in 1802, Paley's book was widely read. While studying for the clergy as a young man, Darwin had read and admired it, not thinking that he would one day be its greatest critic. Fortunately, the two opposing theories can each be tested against the facts. Natural theology predicts that all adaptations should be perfect. Evolution through natural selection predicts that they should be influenced by (and often limited by) the past.



PALEY'S WATCH
William Paley began *Natural Theology* with an example to prove his basic point. He imagined himself walking across a heath and finding a watch among the stones. Unlike the stones, the watch has moving parts that work together for a purpose. The existence of the watch would prove that there was a watchmaker. Paley drew a parallel between a watch and an animal. Just as the watch proved the existence of a watchmaker, so an animal (or a plant) proved the existence of a Creator. By studying natural history, the nature of God could be better understood.

What purpose?

Inspired by natural theology, naturalists set out to find God's intended "purpose" for each living thing, a difficult task, especially in the case of pests such as rats and fleas. In Darwin's view, the only "purpose" of any creature is a private one—to survive and produce young. If it does this, it has succeeded in passing on its characteristics to the next generation.

Faces of leaf-nosed bats

ECHOES OF CREATION?
Bats navigate by making high-pitched sounds and listening for the echoes. Some have elaborate nose-leaves to channel the sound. Can such devices be produced by natural selection, or must there be a "watchmaker," a creator? The fact is that there are many simple versions of this "radar" among bats, and a range of intermediate forms leading up to the most complex ones. This has convinced biologists that such features can, and have, evolved.

European mole

Strong arm for digging

Long, thin hand and finger bones support wing

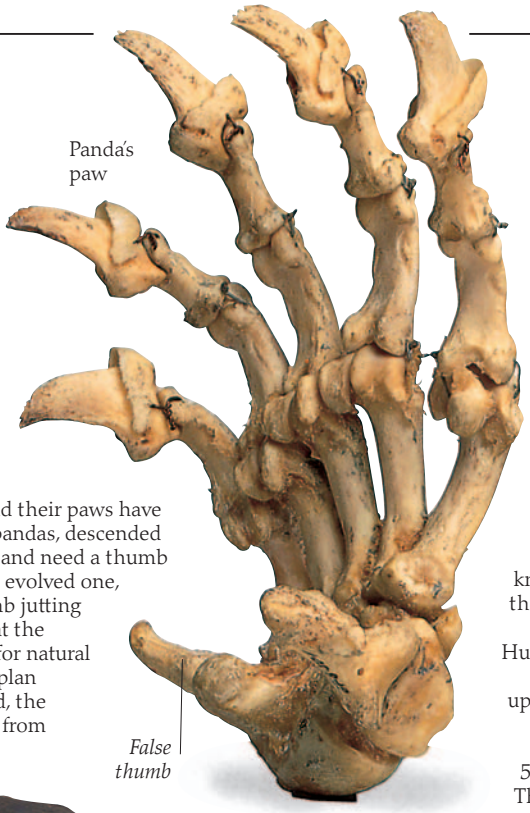
Leaf-nosed bat

SAME BONES
The bat's spreading wing and the mole's stubby digging arm have the same set of bones, as do the arms of all mammals (p. 23). This astonishing similarity only makes sense if Darwin was correct and they come from the same distant ancestor.

Far from perfect

According to Natural Theology, the adaptations of living things should be perfect. According to Darwin, adaptations are always restricted by the ancestry of the plant or animal, because natural selection can only work on the raw material available. If the raw material is not ideal for the purpose, or natural selection has not had long enough to work, the adaptations will be less-than-perfect.

Panda's paw



False thumb

Bears occasionally attack other animals

THE PANDA'S THUMB
Bears are mostly omnivores, and their paws have five very short "fingers." Giant pandas, descended from bears, eat bamboo shoots and need a thumb to hold them. In fact, they have evolved one, but it is a short, imperfect thumb jutting out from the wrist. It seems that the bear's paw was too specialized for natural selection to "reverse" the basic plan and make a true thumb. Instead, the panda's false thumb has grown from a bone in the wrist.

STILL ADAPTING
Many people suffer from backaches, or problems with their hips, knees, or feet, while pain in the arms is rare. In Darwin's terms, this makes sense. Humans are unusual among mammals in standing upright. The fossil evidence suggests that we only began to do so between 5 and 8 million years ago. The human back and legs have not yet had time to adapt fully.

Frigate bird

Giant panda

Human spine

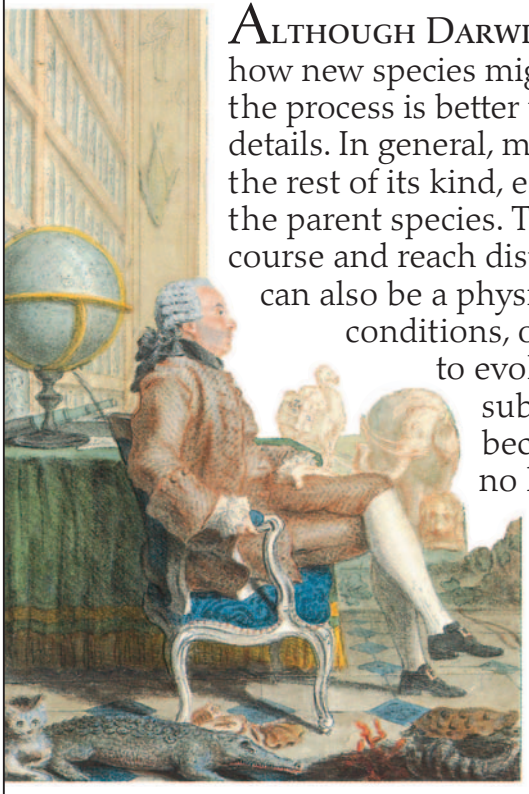
FRIGATE BIRD PUZZLE
Darwin pointed out that both frigate birds and upland geese have webbed feet, yet neither goes into the water. He explained their feet as a leftover from their past, both being descended from waterbirds. If they were designed by a creator, Darwin wondered, why did they have these useless features?

DESIGN FAULT
Loons, or divers, can scarcely walk on land (below), because their legs are set so far back on the body. Most diving birds have the legs set far back, because this is the best position for efficient swimming. The penguin (left) has solved the problem of walking by adopting an upright stance. For the loon, upright walking may evolve in time. A "watchmaker" might have made the loon more mobile on land by standing it upright, or by adding another pair of legs near the middle.

King penguin

Red-throated diver

How new species are formed



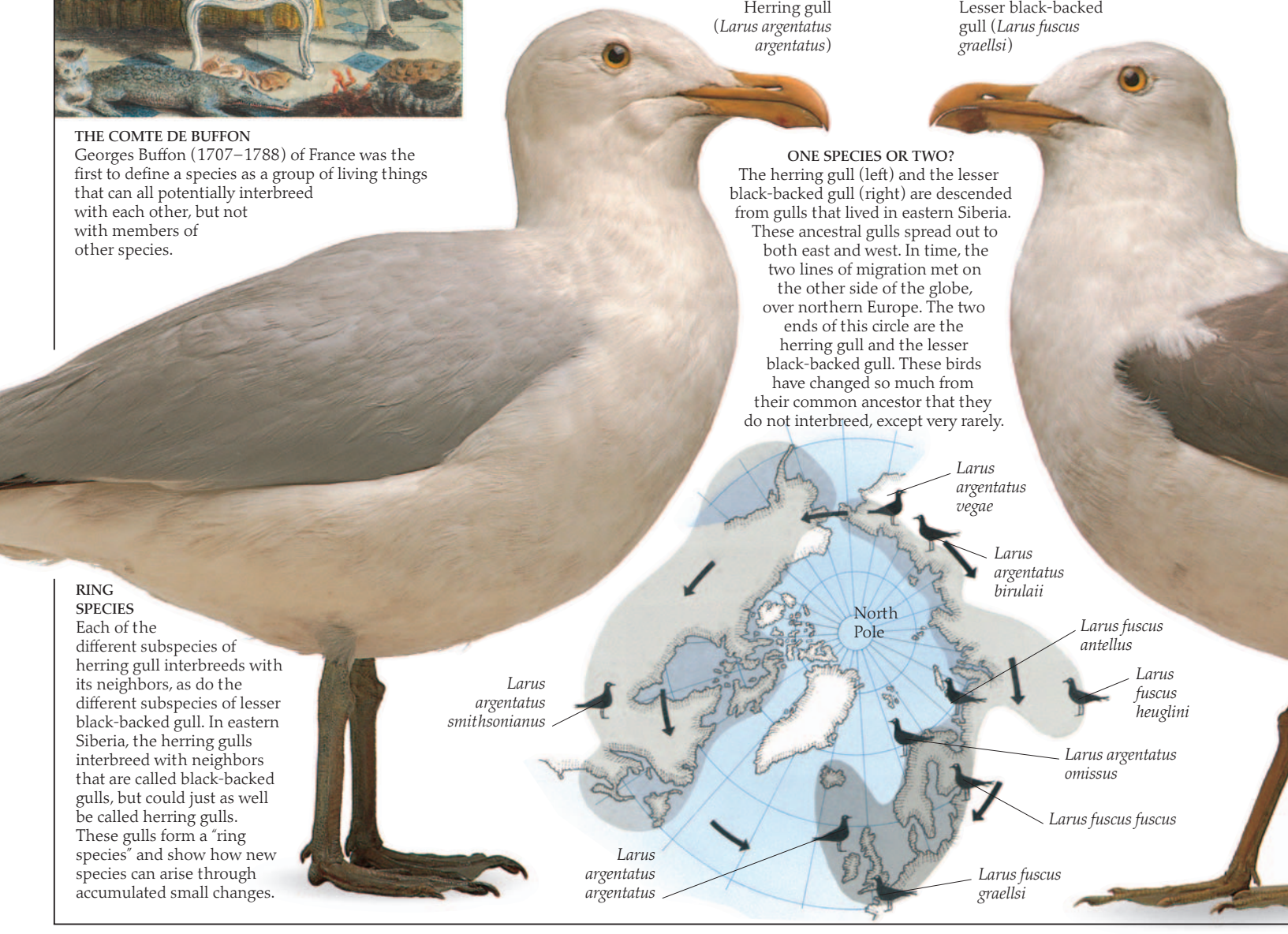
THE COMTE DE BUFFON
Georges Buffon (1707–1788) of France was the first to define a species as a group of living things that can all potentially interbreed with each other, but not with members of other species.

ALTHOUGH DARWIN called his book *The Origin of Species*, he said very little about how new species might arise. In fact, he called this the "mystery of mysteries." Today, the process is better understood, although there are still disagreements about the details. In general, most new species arise when a population becomes cut off from the rest of its kind, especially if it then lives in conditions that differ from those of the parent species. This might happen, for example, when birds are blown off course and reach distant islands (p. 25) or cross a mountain range. Sheer distance can also be a physical barrier, as in the case of a ring species (below). Under new conditions, or simply because they are isolated, the population may begin to evolve in a different direction and may develop into a new race or subspecies. In time, that subspecies can change so much and become so different from the rest of its species that the two can no longer interbreed. Once this happens, they are two distinct species. Occasionally, a new species may arise in other ways, without any geographical isolation.

Herring gull (*Larus argentatus argentatus*)

Lesser black-backed gull (*Larus fuscus graellsi*)

ONE SPECIES OR TWO?
The herring gull (left) and the lesser black-backed gull (right) are descended from gulls that lived in eastern Siberia. These ancestral gulls spread out to both east and west. In time, the two lines of migration met on the other side of the globe, over northern Europe. The two ends of this circle are the herring gull and the lesser black-backed gull. These birds have changed so much from their common ancestor that they do not interbreed, except very rarely.



RING SPECIES
Each of the different subspecies of herring gull interbreeds with its neighbors, as do the different subspecies of lesser black-backed gull. In eastern Siberia, the herring gulls interbreed with neighbors that are called black-backed gulls, but could just as well be called herring gulls. These gulls form a "ring species" and show how new species can arise through accumulated small changes.

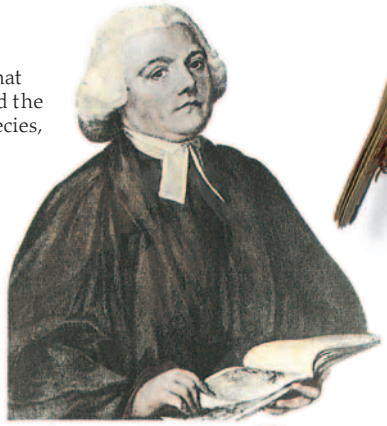
Isolating mechanisms

A new species may develop in isolation, but often it moves back into the area where the "parent" species lives. The two species may still be similar enough to mate and produce young, although these hybrid offspring are infertile (unable to have young themselves). For the parents, producing such a hybrid is a waste of time and energy, so it pays them to recognize their own species. They do so using signals such as smell, sound, color, or behavior. These signals, which keep species apart, are called "isolating mechanisms."

Chiff-chaff

Wood warbler

Willow warbler

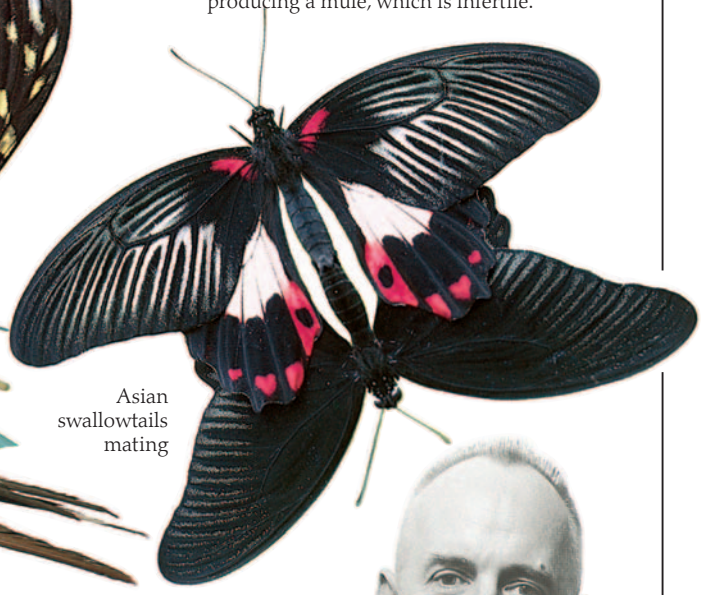


NOT ONE, BUT THREE
The English naturalist Gilbert White (1720–1793) was the first to notice that the chiff-chaff, the willow warbler, and the wood warbler were three different species, and not just one. The wood warbler is slightly larger and brighter in color, but the chiff-chaff and willow warbler look almost exactly the same. The songs of these three, however, are all distinctly different. For the birds, the songs are used by the female to select a mate, so in this way they act as an isolating mechanism, separating the otherwise similar species.

South American Sweet Oil butterflies mating

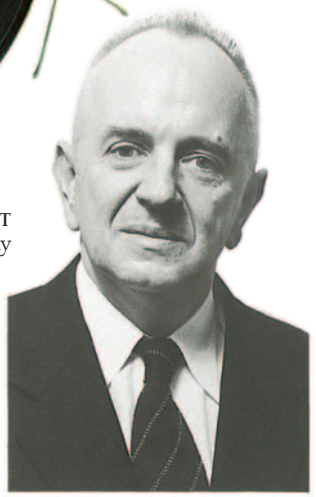
CHOOSING A MATE
Butterflies, which fly by day, recognize potential mates by their patterns and colors. Moths, which fly by night, rely more on scent. For many species, there are also internal mechanisms that prevent fertilization between different species. These are especially important in plants.

GETTING IT RIGHT
These butterflies have made the right choice of mate, but this is not always the case. Mistakes are occasionally made because isolating mechanisms, like adaptations (p. 39), are a product of evolutionary change and are not necessarily perfect. For example, a horse may mate with a donkey, producing a mule, which is infertile.



Asian swallowtails mating

PERFUMED PARTNERS
Mice and many other mammals recognize their own species by characteristic scents. In some species, specific courtship rituals are performed. These are used to confirm that the correct choice of partner has been made.



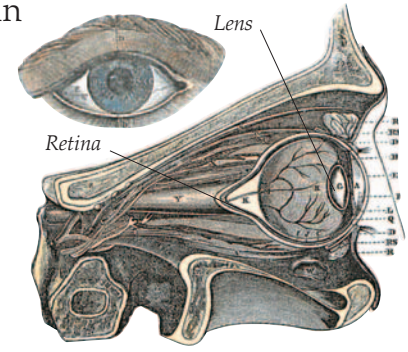
KEPT APART
Theodosius Dobzhansky (1900–1975) worked with T. H. Morgan on fruit flies (p. 51) and helped in the synthesis of genetics and evolutionary theory. He coined the term "isolating mechanisms" for the biological barriers that discourage crossing between different species.

GRADUAL GLIDING
Flying squirrels do not really fly, but glide from tree to tree. Gliding animals could have gradually evolved from ordinary tree-dwellers by acquiring flaps of skin that broke their fall when jumping. Some gliders could then have evolved into flying animals such as birds and bats.

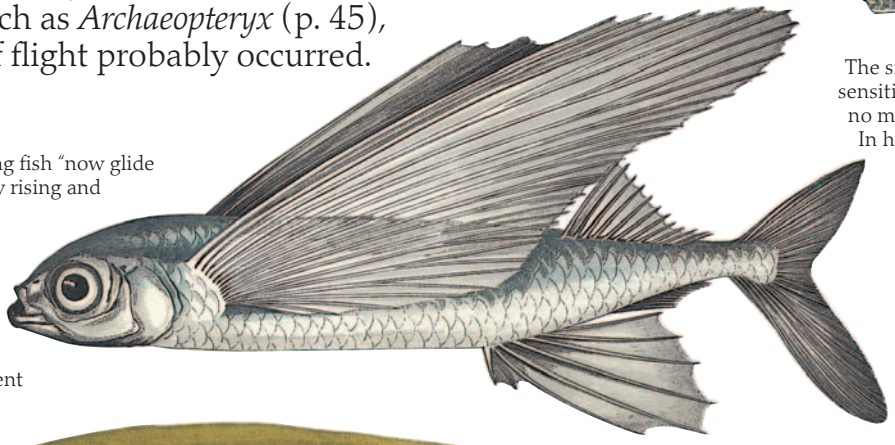
Living intermediates

DARWIN BELIEVED THAT natural selection could produce adaptations (p. 38), but could it produce animals with a completely different way of life? Could it turn a marine animal into a land animal, or a nonflier into a flier? How might such major alterations be achieved through a series of small changes? Some transitional fossils have been found that help to answer this question (p. 44), and "living intermediates" help to make sense of the fossils. These living forms, such as lungfish and egg-laying mammals, are not the ancestors of other animals living today, but they may be related to those ancestors or may have followed a similar evolutionary path. In the case of lungfish, comparisons with fossils show that many extinct lungfish and other air-breathing fish flourished 380 million years ago. The climate was hot and dry, so pools and streams may have been shrinking and stagnant. Lungs must have evolved to allow fish to gulp air at the surface. Fossils show that the evolution of the basic four-limbed (tetrapod) structure developed within a group of fish with paired muscular fins, like those of the Australian lungfish, while they were still mostly aquatic in habit. Thus these fish were preadapted with tetrapod limbs before they used them for life on land. As for any major transition, the move from life in the water onto land required the acquisition of more than one character, namely lungs to breathe air and limbs for movement on land. A similar bit-by-bit transition is seen in birds. New discoveries of feathered and winged but still land-dwelling dinosaurs show how the transition to early birds, such as *Archaeopteryx* (p. 45), and evolution of flight probably occurred.

ASA GRAY (1810–1888)
American evolutionist Asa Gray also considered the problem of intermediates. Darwin wrote to him, "The eye to this day gives me a cold shudder, but when I think of the known fine gradations, my reason tells me I ought to conquer the cold shudder." Objectors to evolution claimed that the human eye could not have evolved by steps, but living intermediates show that it could.



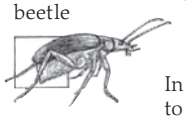
FINE GRADATIONS
The simplest eyes are just clumps of light-sensitive cells. Found in snails, they can do no more than distinguish light from dark. In higher animals, a transparent lens has evolved to focus light on to these light-sensitive cells, which now form the retina.



FLYING FISH
Darwin observed that flying fish "now glide far through the air, slightly rising and turning by the aid of their fluttering fins." If they had evolved into true fliers, Darwin asked, who would then have imagined that "in an early transitional state they had used their incipient organs of flight [fins] exclusively to escape being devoured by other fish?"

AUSTRALIAN LUNGFISH *(below)*
Lungfish, of which there are now only six species, can gulp air at the surface, allowing them to live in stagnant water containing little oxygen. Lungfish and other air-breathing fish flourished 380 million years ago when stagnant pools were probably a common feature of the landscape.

Bombardier beetle



OBJECTION EXPLODED

Bombardier beetles are often claimed as the downfall of Darwinism. For defense, they produce an explosion of hot toxic liquid. Antievolutionists claim that the explosion occurs when two chemicals are mixed, and that each chemical alone is useless. This is incorrect. The chemicals are produced together, and they react only when acted on by enzymes. The chemicals and the enzymes have other uses in living bodies and are not made for this reaction alone. In other words, they were already available to be worked on by natural selection. Likely intermediate stages can be imagined in which toxic liquids were produced but without any explosion.

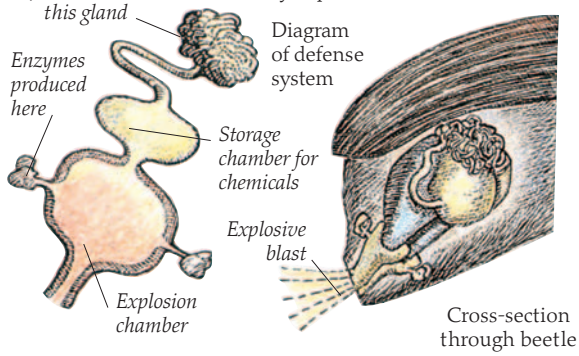
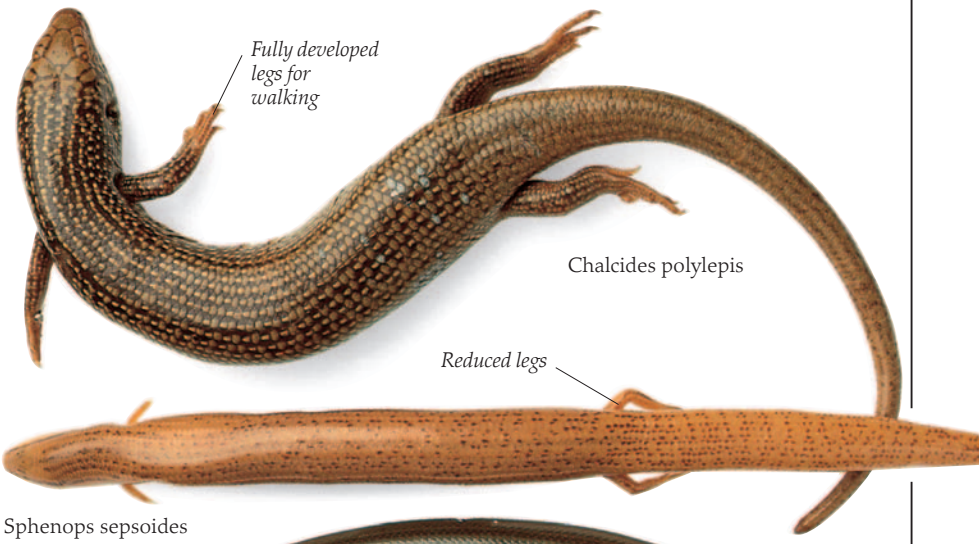


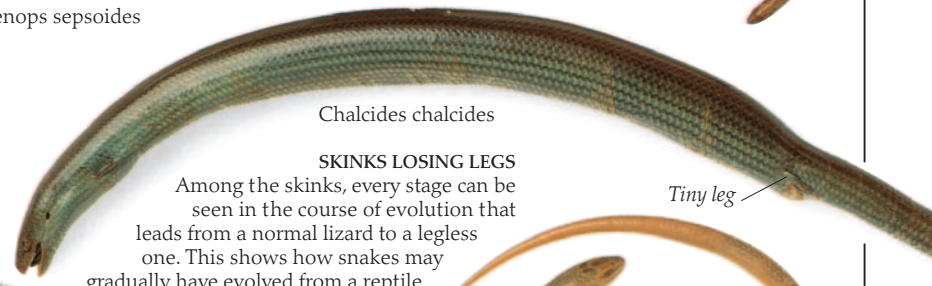
Diagram of defense system

Cross-section through beetle



Chalcides polylepis

Sphenops sepsoides



Chalcides chalcides

SKINS LOSING LEGS

Among the skinks, every stage can be seen in the course of evolution that leads from a normal lizard to a legless one. This shows how snakes may gradually have evolved from a reptile ancestor with legs. The first stage seems to involve the legs getting smaller but remaining useful for running. These skinks can do without their legs when they choose to, and move like a snake. They simply straighten the legs and hold them flat against the body. This allows them to wriggle through long grass, or into a narrow crack in a rock.

Chalcides guentheri

EGG-LAYING MAMMALS

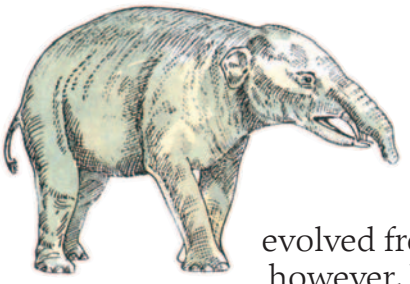
Spiny anteaters are not the direct ancestors of mammals, but they give a good indication of how mammals evolved. They show that being warm-blooded, having fur, and producing milk came before bearing live young. The existence of egg-laying mammals backs up the evidence from fossils (p. 26) that mammals evolved from reptiles. Other sources of evidence, such as comparisons of anatomy (p. 23) or of DNA and proteins (p. 54), tell the same story of a reptile-mammal link. The fact that all the different forms of evidence support each other suggests that evolution is more than just a theory.

Baby spiny anteater in mother's pouch

Spiny anteater

Reptilelike egg of spiny anteater

Fossil intermediates



ANCIENT ELEPHANT
Together with other fossils, the 35-million-year-old fossil *Phiomia* (pictured in this artist's impression) shows how elephants, mammoths, and mastodons evolved from relatively small, hippolike animals.

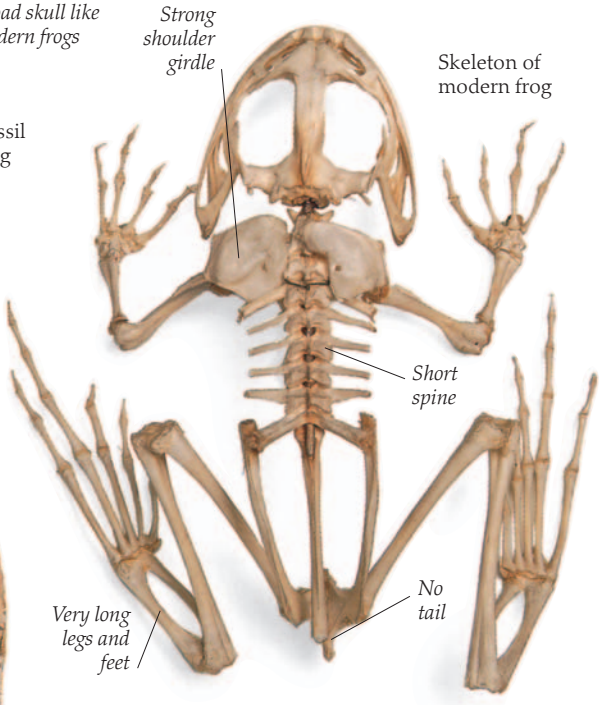
LIKE LIVING INTERMEDIATES (p. 42), fossil intermediates can reveal how new groups evolved from existing ones. They are not a perfect guide, however, because the full set of intermediates is very rarely found. It has been estimated that only one fossil species is found for every 20,000 species that have lived, so the chances of finding an actual ancestor of a living group is very small. The most that scientists can hope for is to find a fossil species that was related to such an ancestor. This means that some guesswork must be used in reconstructing past events. However, the guesses made are based on a great deal of careful study of the fossils, and of living things. All ideas about how things evolved are repeatedly tested and questioned by other scientists. When new fossils are found, they are used to test existing theories about the past and may confirm or disprove those theories. Among the fossils that have helped to reveal the course of evolution are those of early frogs (below). Fossil frogs show that broad skulls came before features such as very long legs. Broad skulls and mouths are typical of animals that catch fast-moving prey under water, so it seems that this led the way in frog evolution.

Artist's impression of *Miacis*, from 50 million years ago

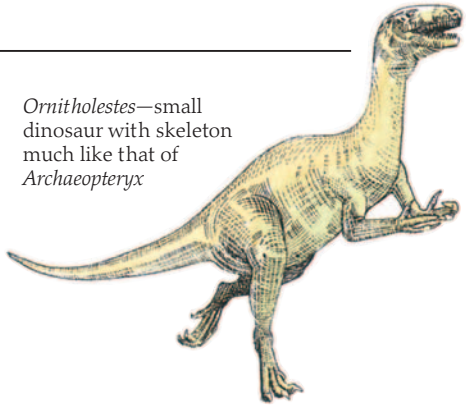
HALFWAY THERE
Fossil skeletons of *Miacis* show that it was on the evolutionary line leading to martens and stoats. Fossils of *Miacis* have been found in coal seams, the remains of ancient dense forests, in Germany.

Artist's impression of 20-million-year-old *Enaliarctos*

ANCIENT SEA DOG
Another fossil, *Enaliarctos*, reveals how doglike ancestors evolved into sea lions. It probably fed in the sea, but spent more time on land than living sea lions.



GREAT LEAP FORWARD
Frogs have specialized skeletons, allowing them to make huge jumps. They evolved from newtlike animals that swam with a side-to-side motion as fish do. On land, they walked. Fossil frogs suggest that jumping did not evolve directly from walking. Early frogs may have begun by catching mobile prey in water. This created a need for fast swimming, which they achieved by kicking with both hind legs at once. Longer legs developed, paving the way for jumping.



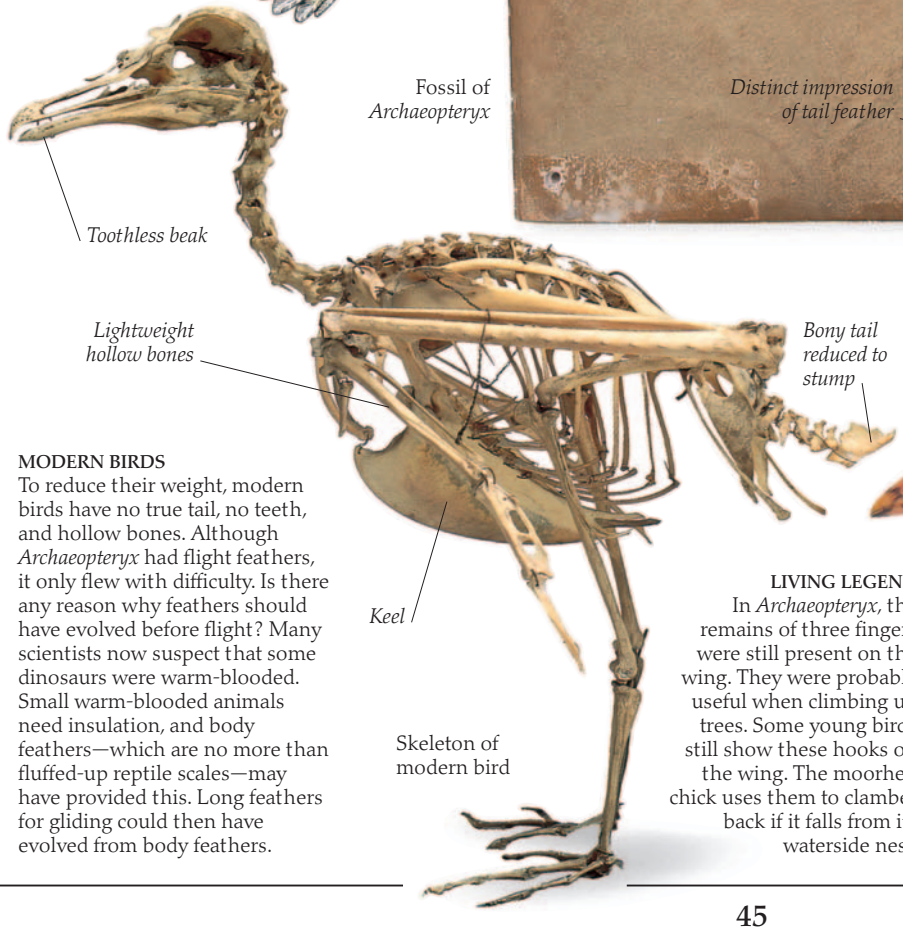
Ornitholestes—small dinosaur with skeleton much like that of *Archaeopteryx*

FROM DINOSAUR TO BIRD

The fossil *Archaeopteryx*, the oldest known bird, is anatomically very similar to small two-legged dinosaurs such as *Compsognathus* but has feather impressions on its wings. *Archaeopteryx* could fly, if not very efficiently. In the late 19th century Thomas Henry Huxley realized that its combination of reptilian features, such as a long bony tail, and bird features, such as the winged structure of its arms, represented one of the first fossil vindications of Darwin's theory of evolution. The discovery of feathered dinosaurs has put the evolution of birds from dinosaurs beyond dispute.

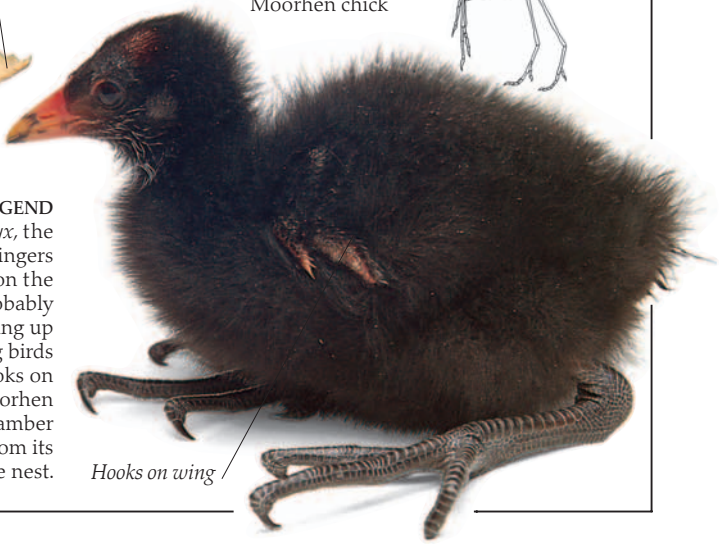
Artist's impression of *Archaeopteryx* gliding

Fossil of *Archaeopteryx*



Dinosaurlike skeleton of *Archaeopteryx*

Moorhen chick



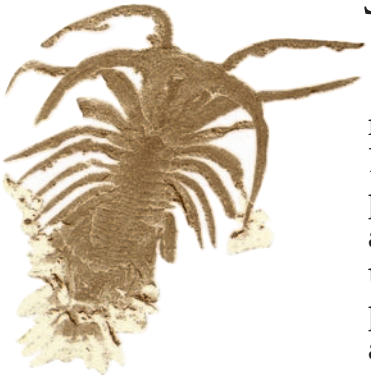
MODERN BIRDS

To reduce their weight, modern birds have no true tail, no teeth, and hollow bones. Although *Archaeopteryx* had flight feathers, it only flew with difficulty. Is there any reason why feathers should have evolved before flight? Many scientists now suspect that some dinosaurs were warm-blooded. Small warm-blooded animals need insulation, and body feathers—which are no more than fluffed-up reptile scales—may have provided this. Long feathers for gliding could then have evolved from body feathers.

LIVING LEGEND

In *Archaeopteryx*, the remains of three fingers were still present on the wing. They were probably useful when climbing up trees. Some young birds still show these hooks on the wing. The moorhen chick uses them to clamber back if it falls from its waterside nest.

Jumps and gaps



THE CAMBRIAN EXPLOSION
This fossil arthropod from the Burgess shale in the Canadian Rocky Mountains belongs to the Cambrian period at the start of the Paleozoic era (below), when many new animals suddenly appeared. No definite ancestors have yet been identified.

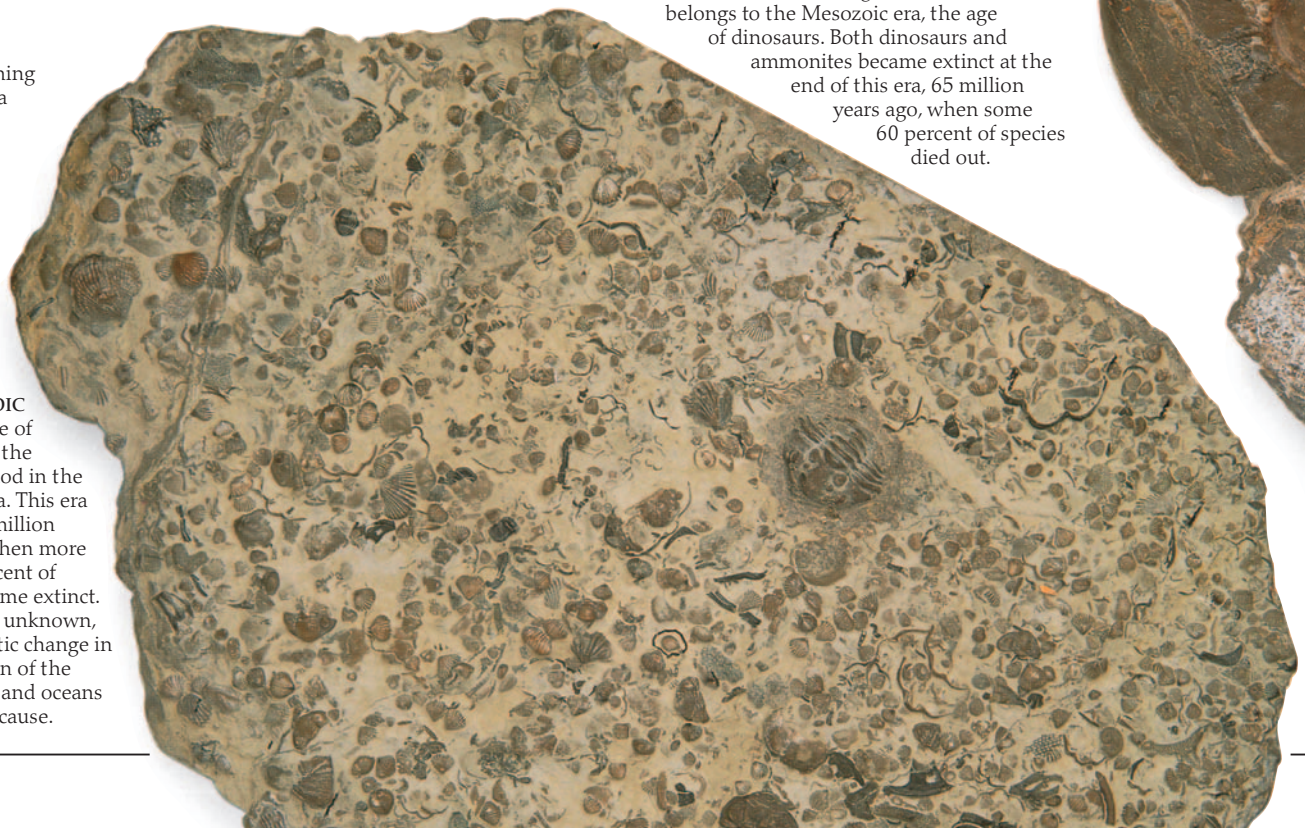
WHILE THERE ARE MANY INTERMEDIATE forms found in the fossil record (pp. 26 and 44), there are also many jumps and gaps. Evolutionists can now explain some of these, but not all. The most puzzling is the sudden appearance of many new and fairly complex animals in the Cambrian period (p. 26). This is still not fully understood, but scientists continue to investigate the issue. A second puzzle, the dramatic changes in fossils at the end of the Paleozoic era and the Mesozoic era, are now fairly well explained (below). A third problem is the lack of intermediates that bridge the gap between many groups, especially invertebrates. It seems that intermediate forms are relatively rare, perhaps because changes occur rapidly, and only in one small area of the world. This would mean that few intermediates become fossils. As a comparison, if a multistory parking garage were "fossilized" by a fall of volcanic ash, there would be plenty of cars fossilized on each level, but the chances of a car being fossilized while driving up from one level to the next would be relatively small.

CHANGING ERAS
As the early geologists noted (p. 16), the fossils from one geological period differ from those of another. The differences between the three major eras (Precambrian, Paleozoic, and Mesozoic) which each include several geological periods (p. 60), are even greater, as these three pieces of fossil-bearing rock show. The major differences between the fossils from successive eras are due to mass extinctions.

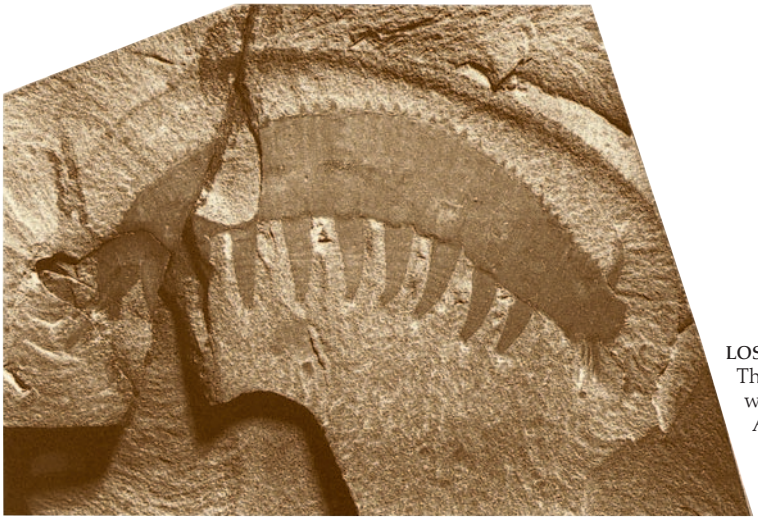
END OF THE MESOZOIC
The Arizona meteorite crater is a recent example of the many impact events that have affected Earth and its life. The Mesozoic Era ended 65 million years ago with a major extinction event, coinciding with a giant 7-mile (11-km) wide meteorite crashing into the Gulf of Mexico. Life was devastated and groups such as the ammonites and dinosaurs died out, except for the small, feathered dinosaurs we know as birds.

2 MESOZOIC
Triassic rock, containing ammonites, belongs to the Mesozoic era, the age of dinosaurs. Both dinosaurs and ammonites became extinct at the end of this era, 65 million years ago, when some 60 percent of species died out.

Rock containing fossilized sea shells and remains of trilobites



1 PALEOZOIC
This piece of rock is from the Silurian period in the Paleozoic era. This era ended 251 million years ago, when more than 90 percent of species became extinct. The cause is unknown, but a dramatic change in the condition of the atmosphere and oceans is the likely cause.



BURGESS BEAST
There is no reason to doubt that Cambrian animals, like this one from the Burgess shale, are descended from Precambrian life. All living things are united by the same basic chemistry and the same genetic code (p. 55).

LOST AND FOUND
The coelacanth is a fish that was thought to be extinct. All the known fossils were more than 200 million years old. Then, in 1938, a live coelacanth was fished out of the ocean. If the coelacanth could survive for 200 million years without leaving any fossils, it is not surprising that some steps in the evolution of life are not recorded.

HARD TO RECOGNIZE
Even when intermediate forms do become fossils, they may not be recognized as such. The dipper (below) dives for its food, but looks like a land bird. Though it may evolve adaptations for underwater life, it has none yet. If dippers were extinct, no one would guess from their fossils how they had lived.

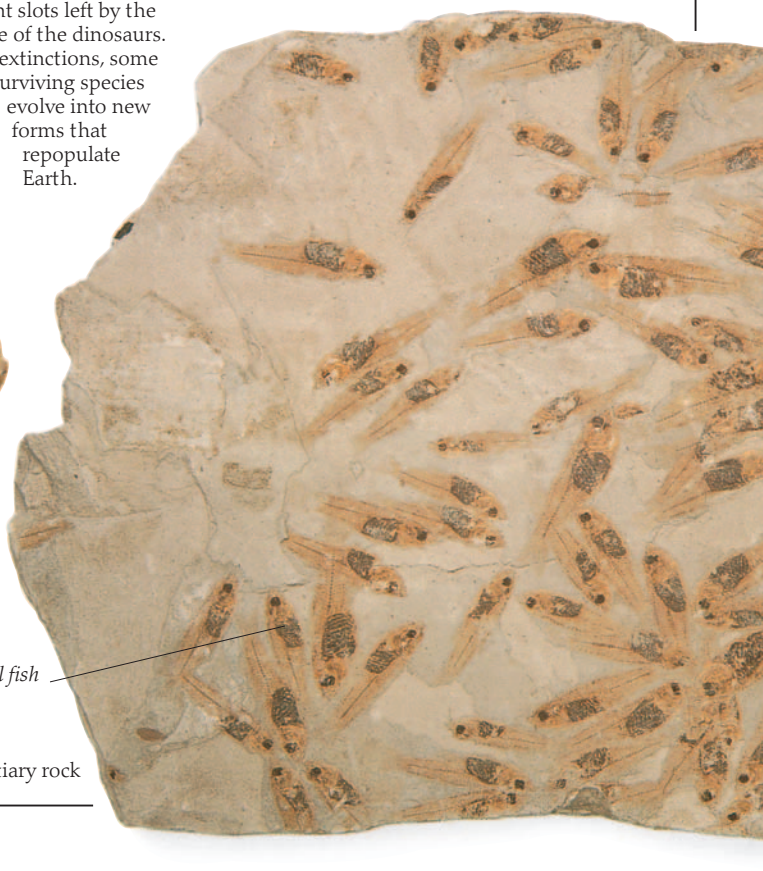
LONG GONE
These soft-bodied creatures from late Precambrian rock (right) lived just before the Cambrian, and are known as the Ediacara fauna. Most scientists think that they are unlikely ancestors for the Cambrian animals, but some disagree.

Fossil imprints of soft-bodied animals (left and below) from the Ediacara Hills in Australia

3 CENOZOIC
This rock (below right), bearing fossil fish, comes from the Tertiary period, part of the Cenozoic era. During the Cenozoic, which is still in progress, mammals and birds have taken over the many vacant slots left by the disappearance of the dinosaurs. After mass extinctions, some surviving species evolve into new forms that repopulate Earth.

Fossil ammonite

Triassic rock



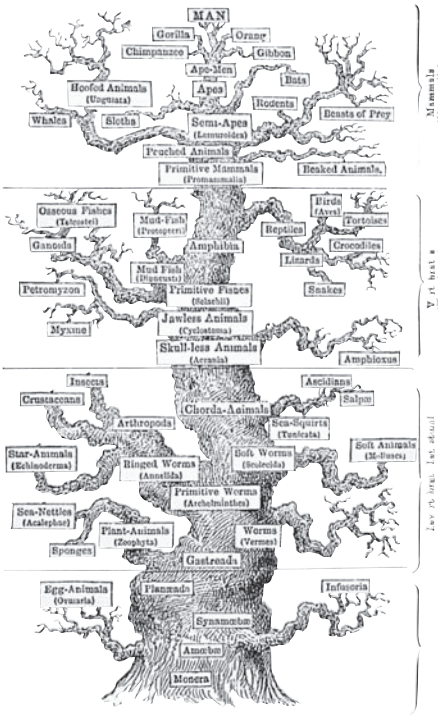
Fossil fish

Tertiary rock

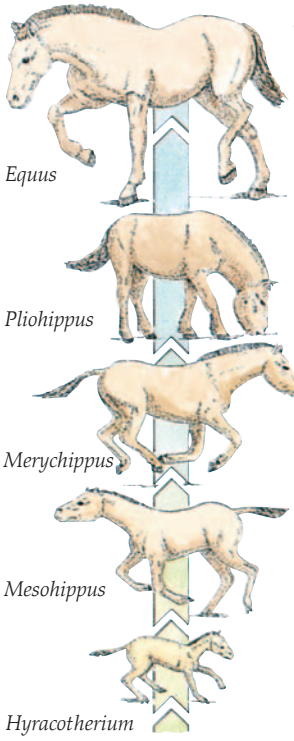
Ladders and branches

ALL FOR PROGRESS
Ernst Haeckel (1834–1919) developed the idea of "evolution as progress" to its fullest extent. He believed that nature had been deliberately moving toward a final goal: human beings. The more that is discovered about what happened in the past, the less this idea makes sense.

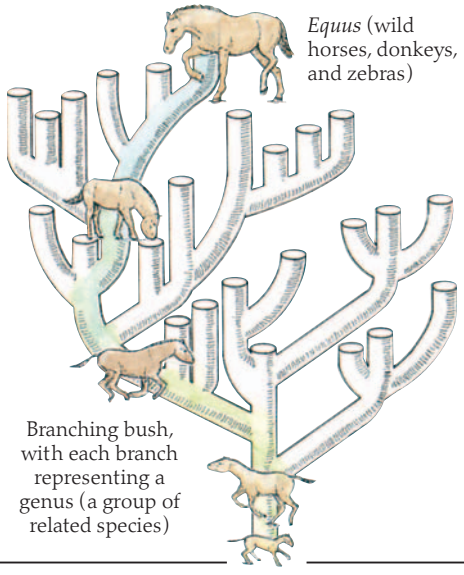
In 19th-century Europe and North America the "Industrial Revolution" was changing everyone's lives. Towns were growing rapidly, a network of railroads was spreading, and new factories were drawing thousands of workers from the countryside to the cities. Almost every aspect of social life was in a process of change. Most people, especially those in power, believed that all these changes amounted to "Progress," and that progress must be good. Evolution was a controversial idea for religious reasons, and linking it to progress made it far more acceptable. Darwin himself refrained from making this connection because he knew that the reality of evolution did not quite fit in with such ideas. For example, many types of bacteria have stayed small and simple for billions of years without "progressing" to become larger or more complex. This is also true of many other living things whose evolutionary history is more like a branching bush of diversification than a ladder of constant improvement. However, Darwin did not try to contradict two of his followers, Thomas Huxley and Ernst Haeckel, both of whom presented evolution in terms of progress. This rapidly became the popular view, and the idea is still widespread today.



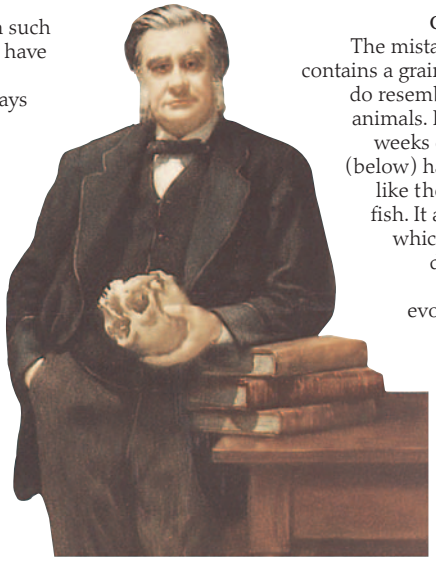
ECHOES OF THE PAST
As well as putting humans at the top, Haeckel's tree contains another of his theories: recapitulation. He believed that as an embryo developed it went through all the evolutionary stages of its ancestors. The five "ancestors" at the bottom of the tree trunk are based on the very early stages of development of an embryo.



GALLOPING UP
The evolution of the horse is often shown by a diagram such as this (left). Although the fossils of all these ancestors have indeed been found, this "ladder" gives a false picture. Evolution does not go in straight lines, and it is not always a steady march of progress from small-and-simple to large-and-complicated. A more realistic image is a densely branching bush (below). There have been dozens of species, most of which have died out, leaving just wild horses, donkeys, and zebras.

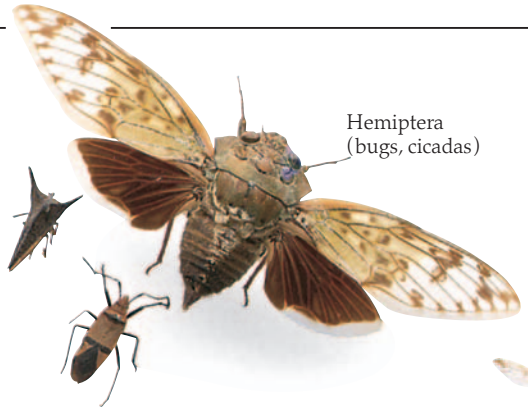


Branching bush, with each branch representing a genus (a group of related species)

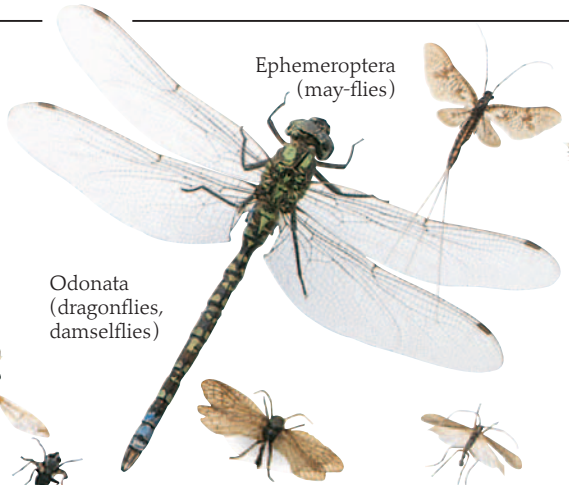


"DARWIN'S BULLDOG"
Thomas H. Huxley (1825–1895) was a young, energetic English scientist who took up the cause of evolution in many public debates. He fought on behalf of Darwin, who preferred to keep out of the public eye. However, Huxley was inspired by Haeckel, and he distorted Darwin's ideas with notions of "progress."

OUR MISSING TAIL *(below)*
The mistaken idea of recapitulation contains a grain of truth. Young embryos do resemble the embryos of related animals. For example, at about four weeks of age the human embryo (below) has a set of parallel grooves like those that lead to gill slits in fish. It also has a tail at this stage, which is later lost. The embryo does develop in a way that sometimes echoes its evolutionary past, but it does not reenact every step of its evolution as Haeckel suggested.



Hemiptera
(bugs, cicadas)



Ephemeroptera
(may-flies)

Odonata
(dragonflies,
damselflies)

A BACKWARD JUMP?
Fleas have no wings and cannot fly, as this microscope image shows, but they evolved from insects that could fly. Why have they lost something that took millions of years to evolve? The answer is that, in the flea's way of life, wings are vulnerable to injury and so are more of a liability than an asset.

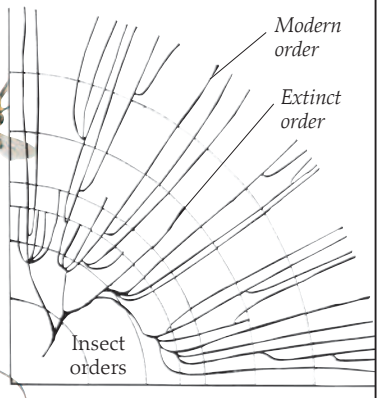
Diptera
(true flies)

Plecoptera
(stone flies)

Trichoptera
(caddis flies)

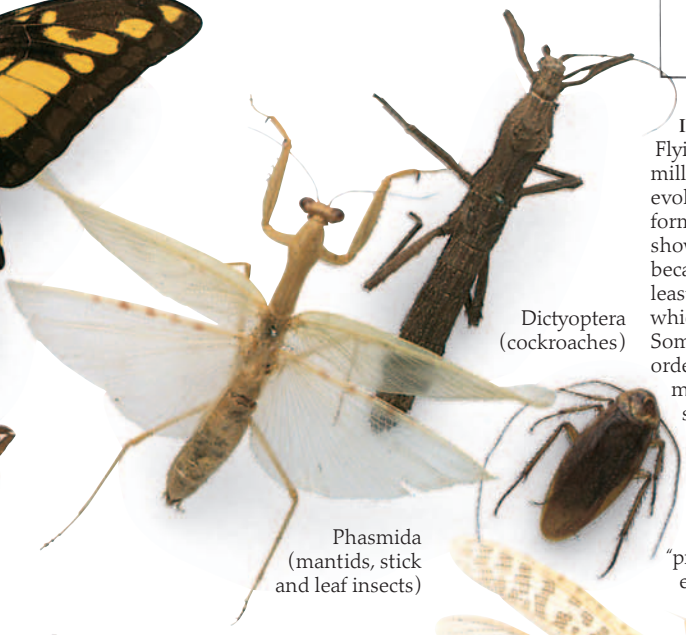
Neuroptera
(lacewings, ant lions)

Hymenoptera (bees,
wasps, ants, parasitic
wasps, sawflies)



Lepidoptera
(butterflies, moths,
skippers)

Dermaptera
(earwigs)



Dictyoptera
(cockroaches)

Phasmida
(mantids, stick
and leaf insects)

INSECT BUSH
Flying insects appeared over 300 million years ago and quickly evolved into a great many different forms. As this evolutionary tree shows, some of the branches became extinct. Today, there are at least 28 different orders of insect, of which 14 are illustrated on this page. Some are extremely varied—the order Coleoptera (beetles) includes more than 300,000 different species. As the flea demonstrates, evolution is not about progress, but about adaptation and survival. Although this often produces an increase in size and complexity, such apparent "progress" is really just a side effect. Some extinct Paleozoic dragonflylike insects had wingspans of 28 in (70 cm) and were the largest insects known.

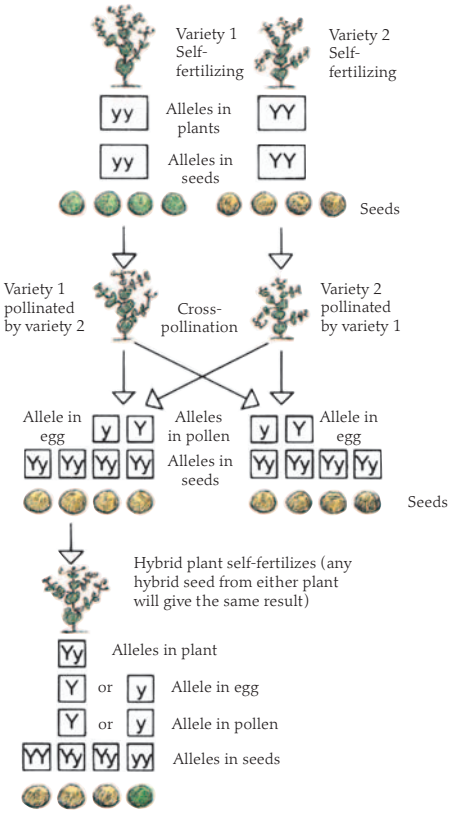
Coleoptera (beetles)

Orthoptera
(grasshoppers, locusts)

Gregor Mendel

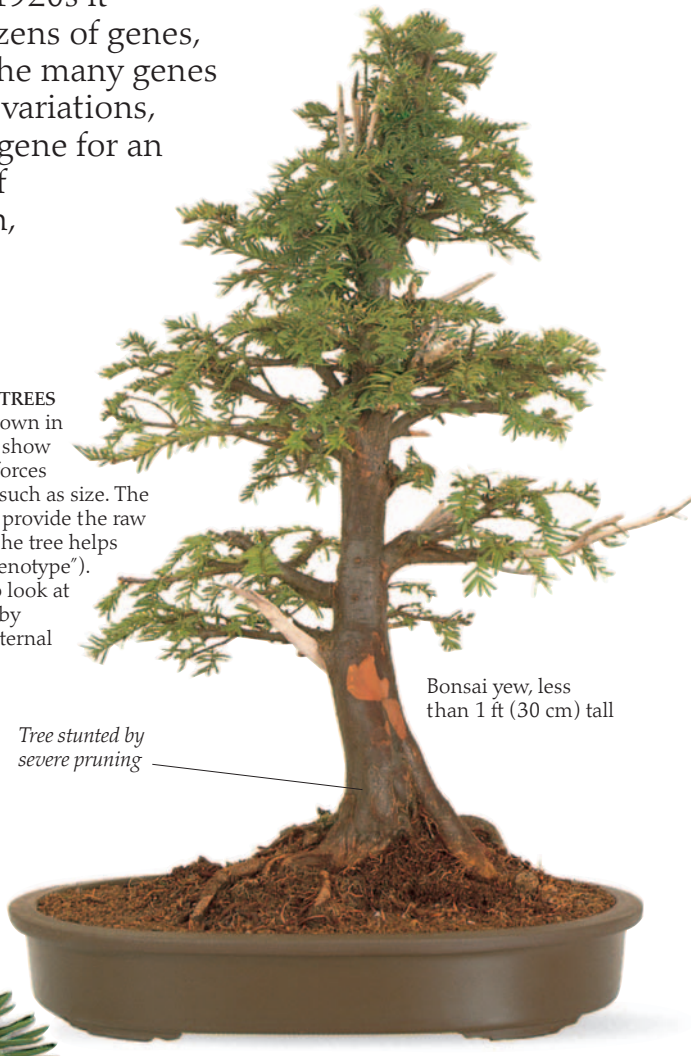
GREGOR MENDEL
The talented and intelligent son of poor peasants, Mendel could continue his science studies only by entering the local monastery. Many of his fellow monks were enthusiastic scientists.

Gregor Mendel (1822–1884) was a monk and a physicist. Some of his fellow monks were crop breeders, and he began investigating heredity to help them to improve their crops. Being a physicist, he looked for simple laws that could be expressed mathematically, and this happened to be a good way of approaching heredity. By an inspired guess, Mendel chose to study "either/or" characteristics, such as seed color in peas. Others scientists were looking at characteristics that appear to blend in the offspring, such as size. Though these are more common, they are far more difficult to study. Mendel's results, published in 1865, were not understood until 1900, when scientists made the same discoveries again. "Mendelism" was born, and in 1909 the word "gene" was coined for his hereditary particles (p. 52). At first Mendelism seemed to oppose Darwinism, because "either/or" characteristics would not create the small variations on which natural selection could work. In the 1920s it was realized that most characteristics are governed by dozens of genes, each with small effects that can add up to a large effect. The many genes controlling a characteristic such as size can provide small variations, but each gene behaves in exactly the same way as a gene for an "either/or" characteristic. The ideas of Mendelism clearly supported Darwin, and they were combined in a new theory—neo-Darwinism.



A branch of normal yew, a tree that grows to a height of 80 ft (25 m)

MINIATURE TREES
Bonsai trees, like trees grown in harsh natural conditions, show how much external forces influence a characteristic such as size. The tree's genes (its "genotype") provide the raw material, but what happens to the tree helps to shape its actual form (the "phenotype"). To study heredity, it is important to look at characteristics that are not affected by external factors, or to keep the external factors exactly the same.



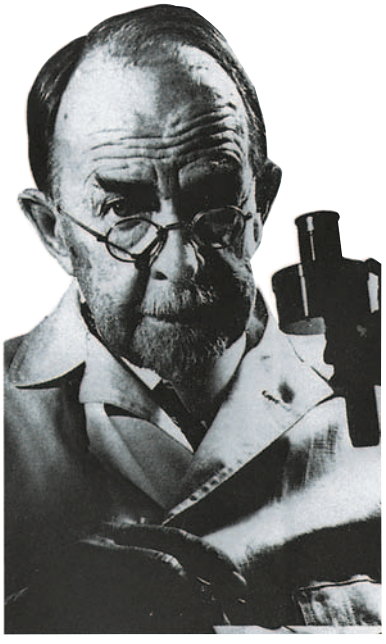
Tree stunted by severe pruning

Bonsai yew, less than 1 ft (30 cm) tall

Finding genes

Mendel worked with plant varieties (different types within a species). He crossed varieties that had distinct, contrasting characteristics, such as seed color. His results showed that heredity was not blending, but involved discrete units, now called genes.

CROSSING PEAS *(left)*
Mendel crossed a green-seeded variety of pea with a yellow one. (Pea flowers normally fertilize themselves, but they can be fertilized by hand with pollen from another plant.) All the seeds from the cross were yellow. These seeds were planted, and the plants were allowed to self-fertilize. They produced yellow and green peas, in a ratio of 3:1. This ratio reveals what is happening inside the plants. As Mendel realized, there must be hereditary particles (now called genes) that do not divide or blend. In this case, there is a single gene for seed color, but two different versions (or alleles) of the gene. One allele codes for yellow, the other for green. Each seed carries two alleles, and if they are of different types then the seed is yellow: the allele for yellow (called the dominant) masks the effect of the allele for green (called the recessive). Each seed receives one allele from the pollen and one allele from the egg.



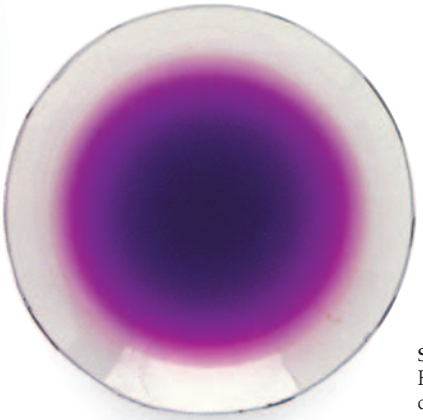
T. H. MORGAN (1866–1945)
Thomas Hunt Morgan began work on fruit flies in 1907. By 1911 he had shown that genes were located on the chromosomes. His work helped lead to the realization that most characteristics are controlled by many genes.

Red ink

Blue ink

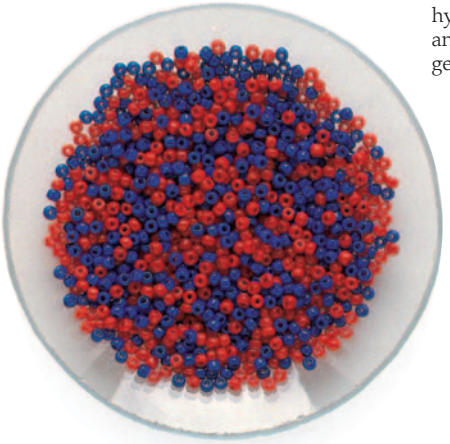
Red beads

Blue beads

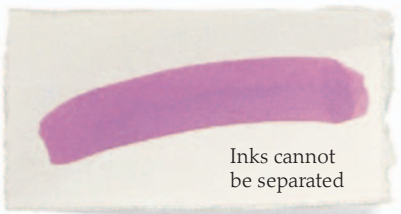


Red and blue inks mixed to produce purple

Red and blue beads mixed to produce purple; each bead represents a single allele of one gene for flower color

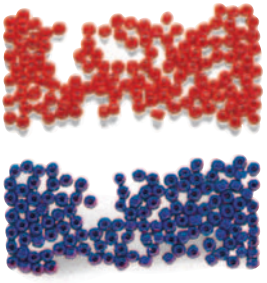


BLENDING QUALITIES
If a plant variety with red flowers is crossed with another variety having blue flowers, the offspring usually have purple flowers. It appears that the effect is like that of mixing inks.



Inks cannot be separated

SEPARATING PARTICLES *(below)*
Heredity actually depends on particles called genes, but for most characteristics dozens of genes are involved, not just one as for the color of peas. Each gene has a small effect, but together they can add up to a large effect. The mixture of red and blue beads shows how the combined action of many genes can give a result that resembles blending inheritance, but this result is only superficial. By breeding from the purple-flowered hybrids, it is possible to get blue plants and red plants again. Like beads, the genes can be separated out again.



Unlike inks, different colored beads can be separated out again

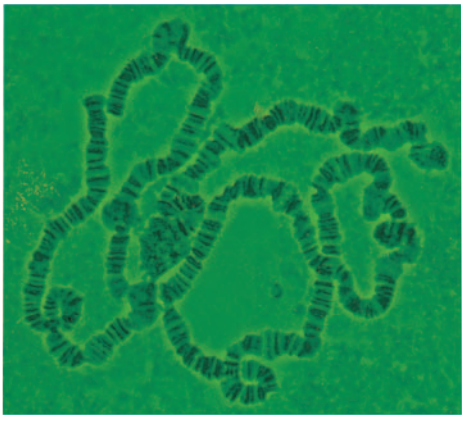
BRED IN BOTTLES
Fruit flies *(Drosophila)* are far easier to study than plants. They can be kept in bottles, they breed quickly, and they often undergo spontaneous changes (called mutations) in their genes. Through his work on these flies, Morgan managed to locate each gene at a specific site, or "locus," on a chromosome. Chromosomes are situated in the nucleus, at the center of every cell.

Normal fly

Tiny mutant fruit fly

This "White Miniature Forked" has three mutations

Normal fly

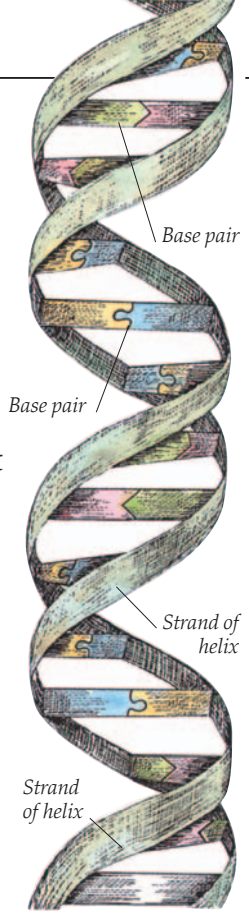


SEEING GENES
Fruit flies offer an added bonus to geneticists—they have giant chromosomes in their salivary glands, and because of their size these can be studied more easily than normal chromosomes. Each band on the chromosomes corresponds to an individual gene site, or "locus." Genes are now known to consist of DNA (p. 52).

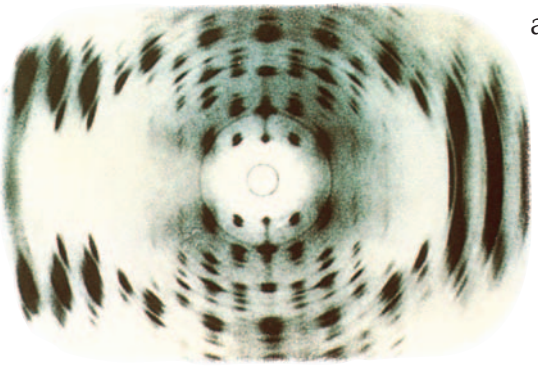
Solving the DNA puzzle

X-RAY VISION
Rosalind Franklin (1921–1958) studied crystals of DNA using X-ray diffraction. The way in which the crystals scatter the X-rays reveals the structure and chemistry of the molecules in the crystal. Rosalind Franklin's images confirmed earlier theories about DNA, that its molecule is indeed a double helix.

By the 1920s, it was clear that the chromosomes (p. 51) carry the genes. Chromosomes were found to contain both deoxyribonucleic acid (DNA) and protein, and no one knew which was the hereditary material. James Watson (b. 1928) and Francis Crick (1916–2004) guessed that it was DNA; they hoped that, by figuring out its structure, they could understand heredity. They had seen X-ray images of DNA, and they knew the shape and chemistry of its various components. Using all this information, they tried to work out the structure by building models. Success came in 1953 and, as they had hoped, the structure revealed how heredity worked. The molecule is like a ladder twisted into a double helix. The rungs of the ladder are made up of chemical compounds called bases, two per rung (called a base pair). There are four different types of base (adenine, cytosine, thymine, and guanine). The breakthrough for Watson and Crick was the realization that adenine could pair only with thymine, and guanine could pair only with cytosine. They saw that this would enable DNA to divide and yet produce perfect copies of itself, and that the order of the bases along the molecule could contain the genetic information.

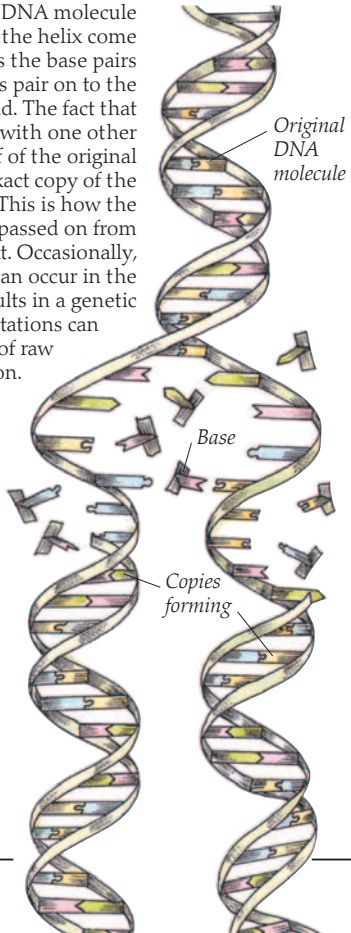


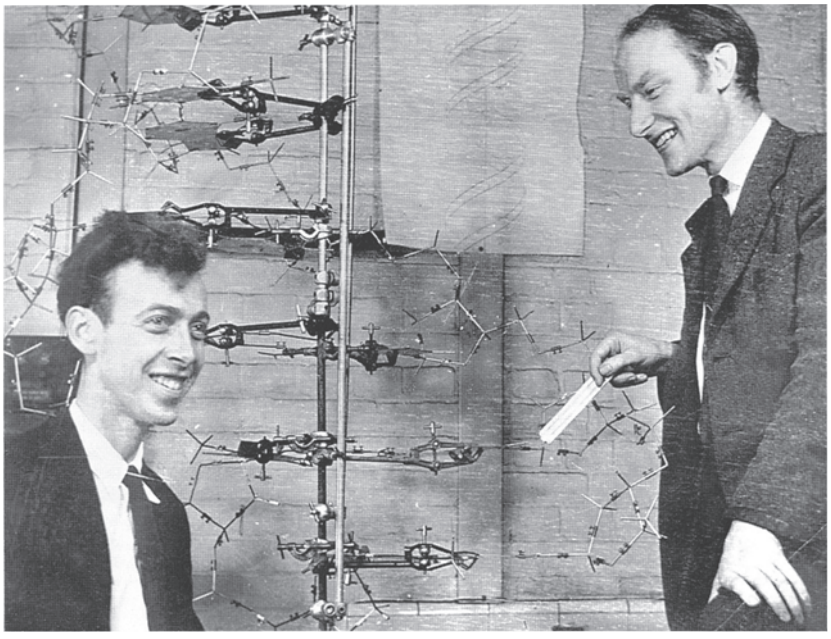
DOUBLE HELIX
This illustration shows the different base pairs that make up the rungs of the DNA molecule. Each base will only fit with one other base.



MAPPING MOLECULES
Rosalind Franklin's X-ray diffraction pictures also revealed that the sugar and phosphate units of DNA were on the outside of the helix. This was vital information for Watson and Crick.

STRANDS OF LIFE
In order to copy itself, the DNA molecule divides. The two strands of the helix come apart, little by little, as the base pairs separate. Then new bases pair on to the existing ones on each strand. The fact that each base can only pair with one other base ensures that each half of the original helix becomes an exact copy of the complete original. This is how the hereditary information is passed on from one generation to the next. Occasionally, however, a mistake can occur in the copying, and this results in a genetic mutation (p. 32). Mutations can provide a valuable source of raw material for evolution.





WINNING MODEL *(left)*
This is part of the original model of the DNA molecule, made by James Watson (left) and Francis Crick (right) in 1953. The base pairs, or rungs, are arranged along the strands of the DNA molecule in what seems like a random order. In fact, the order of the bases is full of information and can be translated according to the "genetic code."

Sugar molecule

Phosphate molecule

Sugar molecule

Base

Base

Linked molecules forming one strand of DNA helix

Second strand of helix

THE GENETIC CODE
This modern model of the DNA double helix shows that the two long strands forming the backbones of the helix are made of identical sugar and phosphate molecules. Only the bases vary. Starting at a particular place on the helix, every group of three bases acts as a "codon" and translates into a particular amino acid. The long string of amino acids that is produced by reading in this way makes up a protein strand. Each gene consists of thousands of bases and codes for one strand of one protein. These proteins include thousands of different enzymes, which control all the chemical reactions taking place in the body. Such reactions produce growth, movement, behavior, digestion, and all other life processes. By issuing its "commands" in the form of enzymes and other proteins, DNA controls every aspect of living things.

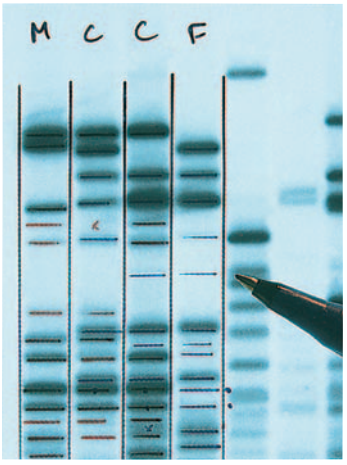
Acorns

TOXIC ACORNS
A difference in their DNA makes European red squirrels less well fed than North American gray squirrels. Gray squirrels have an enzyme that breaks down toxins in acorns, so they can feast on acorns in winter. Red squirrels lack the DNA for this enzyme and cannot benefit as much from acorns. They have almost died out in the UK, largely due to competition from introduced gray squirrels.

INHERITED PATTERN
The coat pattern of the Himalayan rabbit is due to a gene mutation. This causes the enzyme that produces the dark pigment, melanin, to break down when it is warm. The enzyme works only in the cooler parts of the body, such as ears and paws. This means that only these parts have any melanin.

Himalayan rabbit

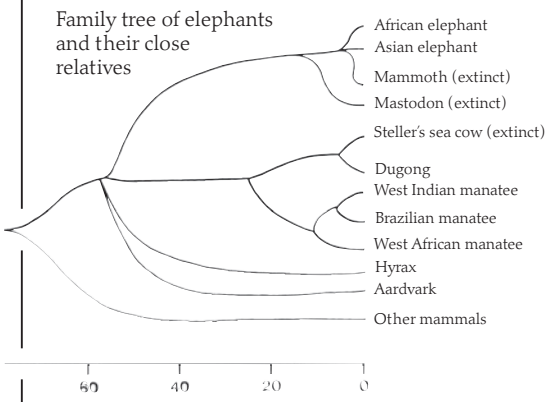
Molecular evidence



DNA FINGERPRINTS
Comparing DNA is a useful way of finding out how closely living things are related. Here DNA from two children (C and C) is being compared with DNA from each of their parents (M and F). This version of the method is called "DNA fingerprinting." It can be used to identify the father of a child, for example. DNA fingerprints can also be taken from blood stains, and these are sometimes used to help in the identification of criminals.

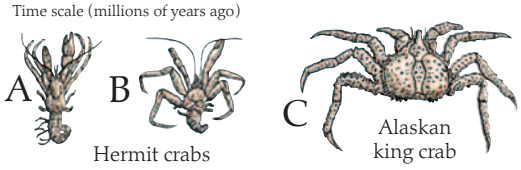
SINCE THE WORK OF Watson and Crick (p. 52), scientists have continued to study DNA. They have found that DNA itself, and the proteins it produces, contain vital evidence about evolution. If two new species evolve from a common ancestor, their DNA, and thus their protein molecules, slowly begin to change and build up differences. The number of differences is proportional to the time since they separated. This discovery was made in the 1960s and a possible explanation was proposed by a Japanese scientist, Motoo Kimura. He suggested that many mutations (p. 32) have neither good nor bad effects. He called these "neutral mutations." Such a mutation could change one of the amino acids in a protein molecule (p. 53) without affecting how the protein does its job in the body. Kimura's theory is still disputed, but the fact that mutations build up at a regular rate is not in doubt. It is as if the molecules inside the body carry a steadily ticking clock that creates a record of the past. This can be used to check the accuracy of evolutionary trees worked out from fossils or from comparisons of the structure of living things. This independent source of evidence largely confirms the evolutionary trees already worked out, indicating that scientific ideas about evolution are correct.

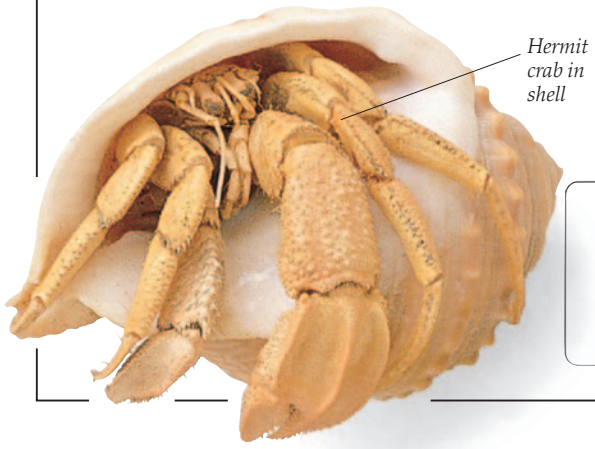
DEEP FROZEN
The bodies of now-extinct mammoths are sometimes found in the icy ground of Siberia. These remains still contain DNA, although it is partially broken down. This ancient DNA can be compared with that of the mammoth's relative, the elephant.

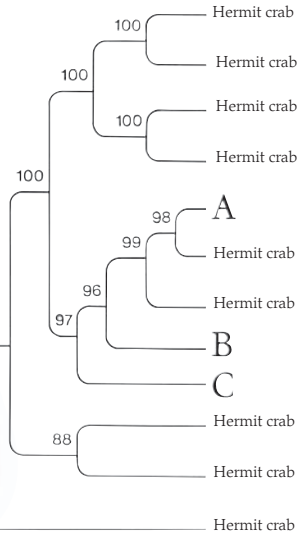


PROTEINS FROM THE PAST
One simple way of comparing proteins is to use the immune system. This is the system that animals have for defense against disease. It reacts to foreign substances very specifically, so if an animal such as a rabbit has been "vaccinated" with proteins from an elephant, its immune system will also react to proteins from a relative of the elephant, for instance a mammoth, but not as strongly. The closer the relationship, the stronger the reaction. The family tree (left) for elephants and their close relatives was worked out in this way.

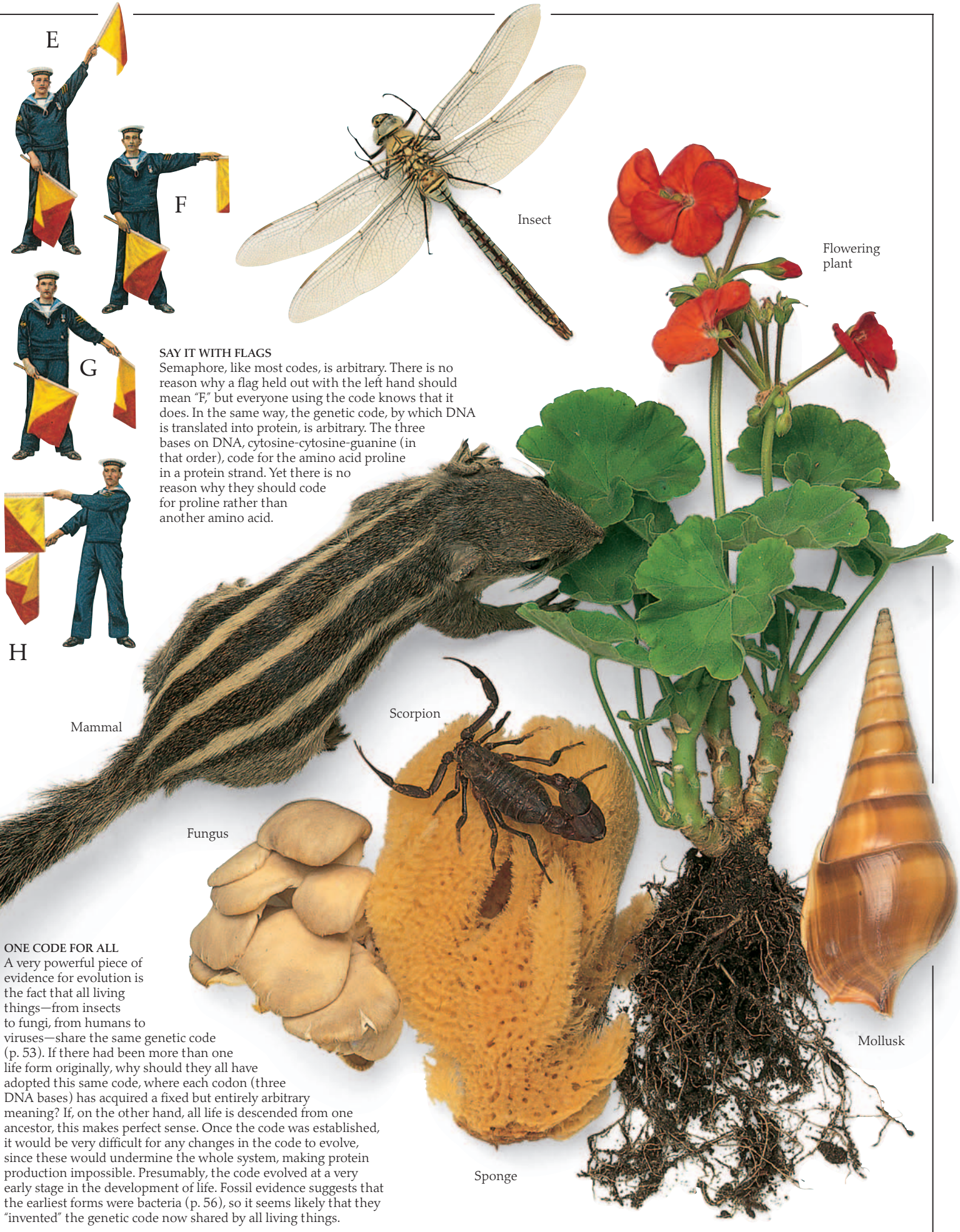
Preserved mammoth from Siberia







TESTING A THEORY
Hermit crabs are small and depend on the shells of mollusks for their homes. Because of their habit of living in spiral shells, the hind part of the body, the abdomen, is curved to one side. Alaskan king crabs are large and never live in mollusk shells, but zoologists suspected that they had evolved from hermit crabs because their abdomens are slightly assymmetrical, like those of hermit crabs. When DNA comparisons became possible, zoologists saw a way of testing this theory. They extracted DNA from many different species of hermit crab and from Alaskan king crabs. Comparisons showed that king crabs are indeed very closely related to the hermit crabs (left). As with the mammoths, elephants, and sea cow, the DNA confirmed what was already thought on the basis of more traditional evidence.



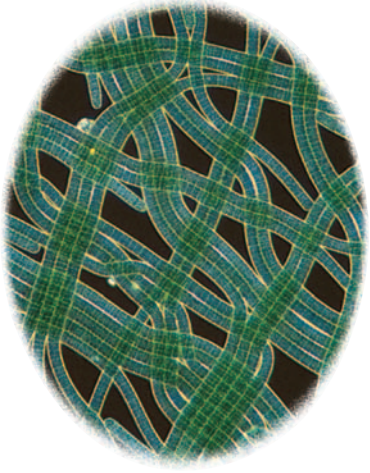
SAY IT WITH FLAGS
Semaphore, like most codes, is arbitrary. There is no reason why a flag held out with the left hand should mean "F," but everyone using the code knows that it does. In the same way, the genetic code, by which DNA is translated into protein, is arbitrary. The three bases on DNA, cytosine-cytosine-guanine (in that order), code for the amino acid proline in a protein strand. Yet there is no reason why they should code for proline rather than another amino acid.

ONE CODE FOR ALL
A very powerful piece of evidence for evolution is the fact that all living things—from insects to fungi, from humans to viruses—share the same genetic code (p. 53). If there had been more than one life form originally, why should they all have adopted this same code, where each codon (three DNA bases) has acquired a fixed but entirely arbitrary meaning? If, on the other hand, all life is descended from one ancestor, this makes perfect sense. Once the code was established, it would be very difficult for any changes in the code to evolve, since these would undermine the whole system, making protein production impossible. Presumably, the code evolved at a very early stage in the development of life. Fossil evidence suggests that the earliest forms were bacteria (p. 56), so it seems likely that they "invented" the genetic code now shared by all living things.

The origin of life

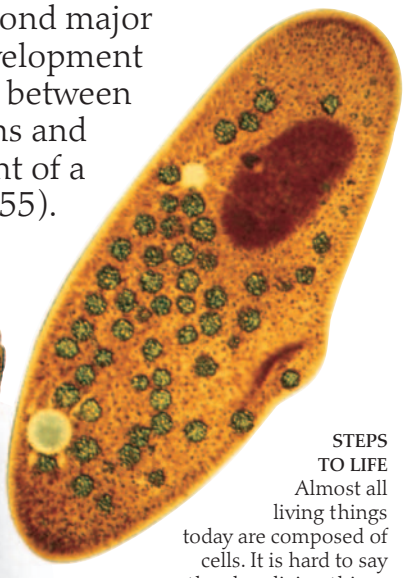
ENERGY INPUT
The chemicals found in living things are far more complex than those found in rocks or sea or air. To create complex molecules from simple ones, energy is required. One likely source of this energy on early Earth was lightning.

How did life begin? Could it have originated from nonliving matter by ordinary chemical processes? The earliest fossils are complex organic molecules 3.8 billion years old. Before that there is no solid evidence about the evolution of life, so scientists have to approach these questions in other ways. One approach is to try to re-create the conditions found on early Earth. Such experiments were first tried in the 1950s and, to most people's surprise, they readily produced the sort of complex chemicals that are found only in living things. These include the building blocks of proteins, DNA and RNA (a molecule that is similar to DNA and is involved in protein production). If complex molecules such as these could have arisen spontaneously billions of years ago, why do they not still do so today? The answer is that conditions now are very different. Most importantly, there is oxygen in the air, whereas there was almost none in Earth's atmosphere then. Once complex chemicals had formed on early Earth, several important steps would have been required before they became genuine living things. Some scientists believe that the first major step was the formation of an RNA molecule that could make exact copies of itself. Recently, small molecules of this kind have been made in the laboratory. A second major step was the development of a relationship between RNA and proteins and the establishment of a genetic code (p. 55).



SELF-SUFFICIENCY BEGINS
The first bacteria must have lived by feeding on the complex chemicals still being produced, but in time they ate more than was being formed. When the supply ran short, many bacteria must have died out, but others, that could make their own food, evolved. These included the cyanobacteria, or blue-green algae (left).

THE OXYGEN REVOLUTION
Some bacteria use energy from the Sun to make their own food, as plants do, and in the process they release oxygen gas. When the first of these bacteria evolved, more than 3.5 billion years ago, they began to produce oxygen, which slowly built up in the air. The oxygen combined with iron in the rocks to produce bands of ironstone (right) at this time. Oxygen changed the conditions on Earth so much that many creatures became extinct. In time, oxygen in the air also allowed new, larger, and more active animals to evolve. Such active life forms would have been impossible without oxygen.



STEPS TO LIFE
Almost all living things today are composed of cells. It is hard to say exactly when living things became cellular. Some theorists suggest that the earliest life forms were "naked" RNA molecules, not surrounded by any membrane. Others believe that a membrane of some sort came first, before RNA. They point out that certain large molecules spontaneously form droplets, inside which other molecules could accumulate.

SEALED UNIT
A cell is a bit like a submarine. The membrane of the cell acts like the hull, creating a sealed unit in which the internal conditions can be closely controlled. Only certain substances are allowed to pass in or out.

The dawn of life?

In the early 1950s an American chemist, Stanley Miller, devised experiments to test ideas about the origin of life. He excluded all oxygen from his apparatus and filled it with methane, ammonia, hydrogen, and water vapor to simulate the atmosphere of ancient Earth. Miller provided an electrical spark to mimic the flashes of lightning that could have provided a source of energy. At the end of the experiment, his apparatus contained complex molecules—the kind of molecules found only in living things. As yet, only one experimenter has managed to persuade these building blocks to join up spontaneously into longer and more complex molecules. Clearly, this was the next crucial step in the evolution of life.

SPARK OF LIFE
In this apparatus, a spark of electrical discharge makes simple gases combine to produce complex molecules such as amino acids (found in proteins).

Electrical supply

Electrode

Tube through which gases circulate

Electrode

EDUCATED GUESSES
Stanley Miller, seen here at work in his laboratory, proposed that gases given off by volcanoes would have helped to create the atmosphere of ancient Earth. Other scientists agree with this, but some have disagreed about the exact gases present. They know that little oxygen was present and that there was probably water vapor in the air, but little else is certain. However, on the basis of educated guesses, several likely combinations of gases have been tried. Almost all of them have been found to produce the complex chemicals typical of living things.

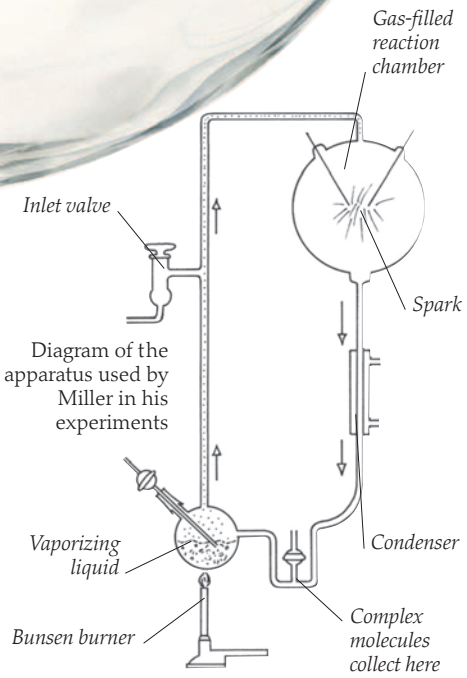


Diagram of the apparatus used by Miller in his experiments

Science and belief

APE OR ANGEL?
A 19th-century French cartoon shows Darwin in apelike form, bursting through the hoops of credulity and ignorance held by the French physician and philosopher Maximilien Littré (1801–1881), a supporter of Darwin. The evidence that humans arose from apelike ancestors by evolution is very strong (p. 63), but this idea troubles many people. Alfred Wallace (p. 36) solved his dilemma between science and belief by proposing that, while human beings had indeed evolved, the human spirit came from some supernatural source.

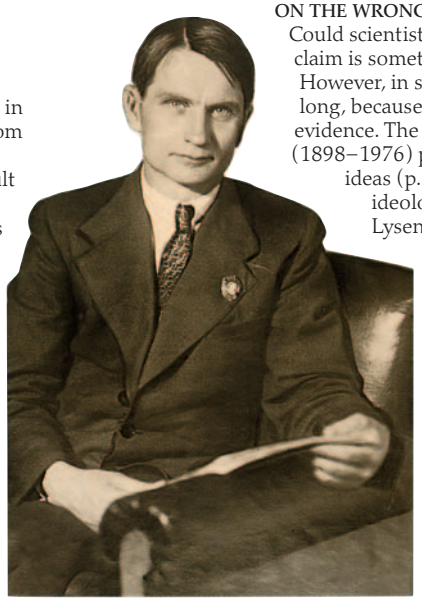
MANY DIFFERENT CULTURES have traditional beliefs about how the living world was made (p. 6). These beliefs are not usually open to question or change. Scientific ideas about the history of life are different: the details of the story are continually changing because scientists work by looking for new evidence, by questioning existing theories and trying to develop better theories. In time, some theories become well established, and their basic points are accepted as fact simply because the evidence in their favor is overwhelming. The idea that the Earth goes raound the Sun is one such theory. The idea that evolution has occurred is another. There may still be arguments over the details of how evolution occurred, but the fact that it did occur is not in doubt among scientists. One way of testing theories is to use them to make predictions and then to check those predictions. Because evolution proceeds so slowly, it is more difficult to test in this way than other scientific theories. (For the same reason, we do not normally notice evolution in action around us, even though it is continuing all the time.) Occasionally, however, evolutionary theories can be tested in the wild.
A theory about how social insects evolved was used to make a prediction about evolution in mammals, and this was later confirmed by discoveries about the naked mole rat. Theories about natural selection were tested by observing the effects of cleaner air on the peppered moth.

SCIENCE AND THE PRESS
Stephen Jay Gould (1941–2002) was among the scientists who continually tested and questioned the details of evolution theory. Sadly, newspapers often fail to understand this scientific process and assume that the whole idea of evolution is in doubt. They then report the scientific debates under dramatic and misleading headlines, such as the one below.

Darwin Wrong Scientist Claims

by our Science Correspondent

CLEANER AIR, PALER MOTHS
A dark form of the peppered moth replaced the paler form in industrial areas of England from the 1850s onward. Scientists suspected that this was a result of pollution reducing the camouflage of the pale moths (p. 36). Natural selection by moth-eating birds was thought to be at work. When, in the 1970s, laws were passed to reduce pollution, an unintentional "experiment" took place, allowing scientists to check their theory about why the darker form had taken over. In the next few years the air became cleaner. As predicted, the numbers of dark moths did fall, while the paler ones increased.



ON THE WRONG TRACK?
Could scientists be totally mistaken about evolution? This claim is sometimes made by opponents of the theory. However, in science, mistaken ideas do not survive for long, because theories are tested against experimental evidence. The case of Soviet geneticist Trofim Lysenko (1898–1976) proved this point. He favored Lamarckian ideas (p. 13), since they agreed with Communist ideology, and he rose to power under Stalin. Lysenko banished Mendelian geneticists (p. 50), and dominated Soviet genetics for many years. Eventually, however, the evidence against Lamarckian inheritance was so strong that ideology had to give way to science. Lysenko was discredited and forced to resign.

Puzzle and prediction

Social insects, such as bees, wasps, and ants, live in colonies in which a single female produces all the offspring while the other members of the colony carry out duties of protection and feeding. How such social insects could have evolved has long been a puzzle. In the 1970s, the American zoologist Richard Alexander proposed an answer. He suggested that an insect species that cares for its young might evolve into a social insect as a direct result of living in a "fortress of food"—a well-defended nest to which food can be imported, or in which food is already available. He also made the bold prediction that a social mammal could evolve to live like these insects.

WASP NEST
Wasps are social insects, like bees and termites. Each colony builds a complex nest, and at the center of this nest, one female can remain safe and well fed. She produces all the young. The other wasps defend the colony or go out to collect food. Even if they are killed, their genes are passed on to the next generation, because the queen shares those genes. Until 1976, this odd way of life was known only among insects.

Naked mole rat hills formed during tunneling

THE UNLIKELY MAMMAL
Alexander suggested that a mammal with a social life like a bee could have evolved. He predicted that if it did so, it would probably live in a place with a long dry season, where some plants have huge tubers. The mammal would be a burrower that could build its underground colony—its "fortress of food"—around these tubers. Several years later, to the amazement of scientists, South African zoologist Jennifer Jarvis revealed that the naked mole rat, an East African mammal, lives precisely as Richard Alexander had predicted.

Worker gathering food

DIGGING BLINDLY
Like a worker wasp, the naked mole rat worker spends its time defending the colony, bringing food to the young, or tunneling through the ground to find the tubers on which the colony feeds. While digging, it can close its mouth behind its front teeth, to keep from swallowing soil. It is almost blind, rarely venturing into daylight.

Naked mole rat queen in burrow

UNDERGROUND QUEEN
The queen is the only mole rat in the colony to produce offspring. She keeps the other females infertile by her dominant behavior. She remains in the safety of the deepest part of the burrow (above) and is vigorously protected by the workers. In the nest chamber she suckles the young (right) until they are old enough to be fed on tubers by the workers.

DISPOSABLE WORKER
The workers live and die without producing any young. When the colony is under attack by a snake, workers may sacrifice their own lives in order to defend the colony, just as worker bees do.

Baby naked mole rats suckle at the queen's teats

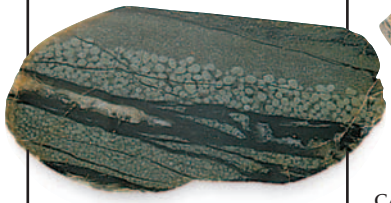
Naked mole rat worker

The queen is larger than the workers

History of life

THE SCIENTIFIC STUDY of rocks, fossils, and living things can be used to build up a picture of what happened in the past. Hundreds of scientists, working in different parts of the world, have helped to build up this picture. The details change as new evidence is constantly being found, and there are differences of opinion among scientists about some of the specific points. However, there is broad agreement on the major events, the general course of evolution, and the time-scale.

BEFORE LIFE
Meteorites were formed at the same time as Earth (p. 29). Earth's crust solidified 4.5 billion years ago, but for millions of years Earth was empty of life. Although the early steps in the origin of life can only be guessed at (p. 56), the first fossils of bacteria are some 3.5 billion years old.



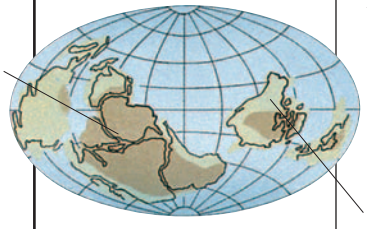
BACTERIAL FOSSILS
Bacteria evolved into many types with different ways of obtaining their food. Some cyanobacteria (p. 56) form colonies that are large enough to be seen without the aid of a microscope.

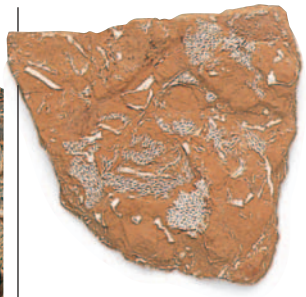
GETTING LARGER
Only at the end of the Precambrian do readily visible, larger life forms appear. Most belong to the Ediacaran fauna (p. 47).

CAMBRIAN EXPLOSION
In the early Cambrian, many different kinds of complex marine animals suddenly appear in the fossil record.

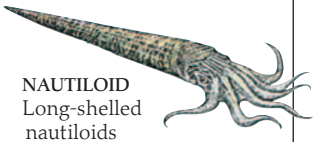
BURGESS SHALE
Cambrian rocks reveal many different groups of invertebrate animals.

PLATE MOVEMENT
Over geological time, the movement of crustal plates has caused oceans to open and close and carried continents over Earth's surface.

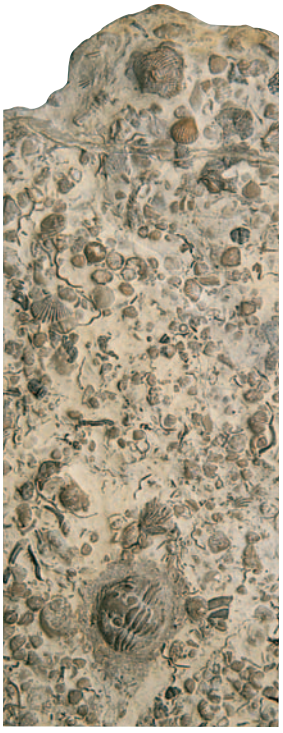




SIMPLE SURVIVORS
In this fossil colony of bryozoans, each opening contained a single tiny animal. Still found today, bryozoans have shown little change for millions of years, like many other simple creatures.



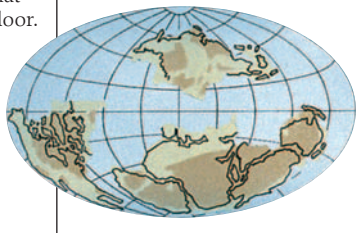
NAUTILOID
Long-shelled nautiloids such as *Orthoceras* (p. 27) were among the invertebrate animals that inhabited the seas of the early Paleozoic era.



SILURIAN SEAS
Primitive arthropods known as trilobites were abundant and widespread during the Ordovician and Silurian periods. Fossils of feeding tracks show that they lived on the seafloor. They later became extinct, as did the giant sea scorpions, large armored animals up to 6 ft (2 m) long, with huge pincers.

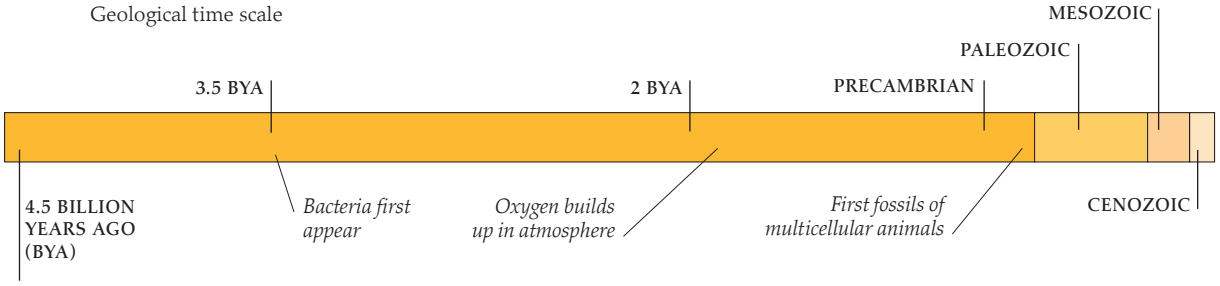
ARMORED FISH
Many of the early jawless fish were covered in plates of bony armor, probably as a defense against the giant sea scorpions..

AGE OF FISH
During Devonian times some land masses were joined together to form larger continents with vast dry regions and large rivers and lakes. With seasonal and dry climates, many waters were prone to dry out. These conditions favored the survival of groups of fish that could breathe air and use their muscular fins and limbs to move from one body of water to another.



PRECAMBRIAN	CAMBRIAN PERIOD	ORDOVICIAN PERIOD	SILURIAN PERIOD	DEVONIAN PERIOD
	PALEOZOIC ERA			

TIME SPAN
Most of the history of life is taken up by simple single-celled animals, largely bacteria. They were the only living things for almost 3 billion years. Compared with this, the extinction of the dinosaurs at the end of the Mesozoic, 65 million years ago, seems like a fairly recent event, as does the emergence of modern humans, just 100,000 years ago.

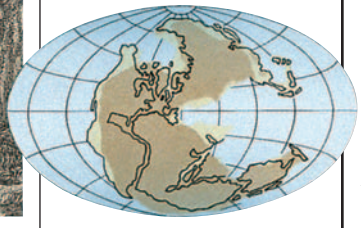


FOSSIL FERN
Plants, like animals, evolved from bacterial ancestors, probably during the late Precambrian. The simplest plants were one-celled algae. From these evolved seaweeds, mosses, ferns, trees, and all other plants, past and present.

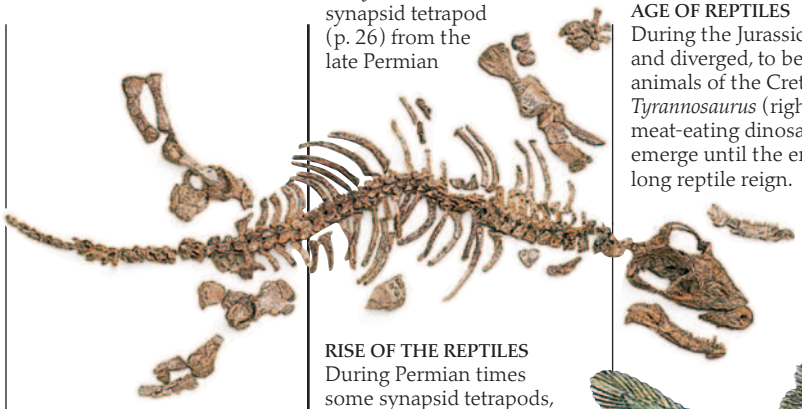
LIFE ON LAND
Life existed in the sea until late Ordovician times, when primitive land plants such as lichens and mosses evolved. The first true land plants evolved in Silurian times, becoming tree-sized in late Devonian and Carboniferous times.

STRANGE FOSSIL
The arrow-headed amphibian *Diplocaulus* lived during the Permian. The legs of this fossil are missing.

SUPERCONTINENT
At the end of the Permian, more than 90 percent of all species died out, the largest mass extinction (p. 46) of all time. During the Permian, all the continents collided to form one supercontinent, called Pangea.



Procynosuchus, a synapsid tetrapod (p. 26) from the late Permian



RISE OF THE REPTILES
During Permian times some synapsid tetrapods, known as cynodonts, evolved mammal-like features and became widespread and abundant. Many died out at the end of the Permian, along with many other tetrapods. This cleared the way for a new phase of reptile evolution. New synapsid groups appeared and flourished during the Triassic, along with the ancestors of dinosaurs.

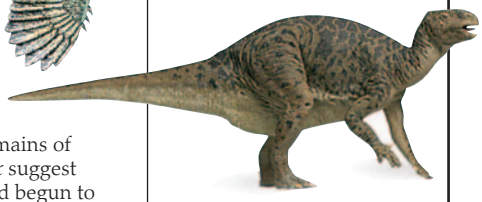
SPIRAL SURVIVORS
By the Triassic, most nautiloids had tightly coiled shells. The more specialized ammonites became extinct at the end of the Cretaceous, but some nautiloids survived.

AGE OF REPTILES
During the Jurassic, the dinosaurs expanded and diverged, to become the dominant land animals of the Cretaceous period. *Tyrannosaurus* (right), a large meat-eating dinosaur, did not emerge until the end of this long reptile reign.

EARLY BIRD
The fossil remains of *Archaeopteryx* suggest that birds had begun to evolve from dinosaurs during the Jurassic.

FOSSIL FROG
Recent discoveries show that modern amphibians such as salamanders and frogs originated in the Permian era, and caecilian (wormlike) amphibians in Carboniferous times.

VEGETARIAN DINOSAUR
Iguanodon (below), a plant-eating dinosaur, was common in the mid-Cretaceous but then died out. Throughout this period, many new species of dinosaur evolved, but all had died out by the end of it.

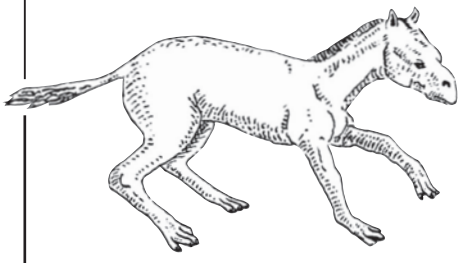


CHANGING WORLD
By the end of the Cretaceous, the single supercontinent had split up, and the continents were moving apart toward their present positions. At the end of this era there was a mass extinction in which all the dinosaurs and many other animal species died out.

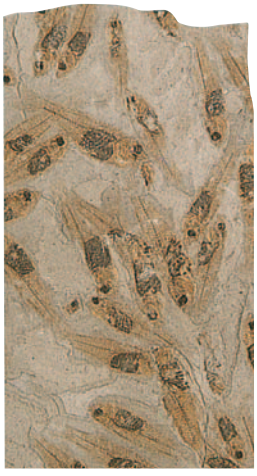
CARBONIFEROUS PERIOD	PERMIAN PERIOD	TRIASSIC PERIOD	JURASSIC PERIOD	CRETACEOUS PERIOD
PALEOZOIC ERA		MESOZOIC ERA		

Up to the present

FOR THE PAST 65 MILLION YEARS, mammals have been the dominant land animals. Their ancestors were small nocturnal creatures that evolved 200 million years ago from the synapsid tetrapods (p. 26). During the age of dinosaurs, they remained small but began to diversify with aquatic and gliding forms. Some preyed upon small dinosaurs. After the dinosaurs' extinction, mammals evolved rapidly, growing larger and more diverse. So too did the birds, but their bones are fragile, so there are relatively few in the fossil record.



EARLY HORSE
Hyracotherium is one of the earliest horse-like mammals from 55 million years ago. The fact that evolution is not a steady march of progress is well illustrated by the horse (p. 48) and by mammal evolution in general. There has, however, been an increase in speed, intelligence, or size, in some mammal lines.



SEAL FORERUNNER
Many of the early mammals were a bit like dogs in shape and build. They gradually evolved into more specialized forms, such as seals, deer, and horses.

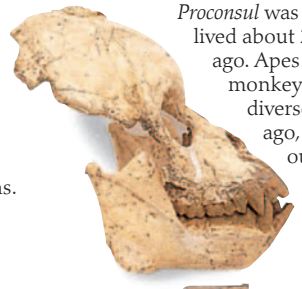
MIGHTY MASTODON
This vertebra (below) is from a mastodon (p. 14), an elephantlike animal that browsed on trees. The American mastodon survived into the Quaternary period and only died out about 10,000 years ago. Like many other large mammals that died out at this time, it may have fallen victim to human hunters.

ICE AGE BEAR
This cave bear skull is about 20,000 years old. These large bears lived during the last Ice Age and survived the extreme cold of winter by hibernating in caves. Mammals from the Quaternary period were more like present-day mammals than were those of the Tertiary, but many were far larger than their modern relatives.

END OF THE LINE
The extinct *Palaeotherium* is known from this jaw and other fossils. It was a tapirlike animal.

FISH AND PLANTS
It is not only the dominant animals (such as mammals) that continue to evolve, although this is the part of the story that attracts most interest. During the Cenozoic, there has been change among fish (above) and plants (left), as well as other living things.

ALMOST AN ELEPHANT
The fossil known as *Phiomia* is part of the group that later gave rise to elephants, mammoths, and mastodons.



ANCIENT APE
Proconsul was an early ape that lived about 20 million years ago. Apes evolved from monkeys. They were very diverse 20 million years ago, but many died out as Earth's climate grew drier and the forests shrank.

VANISHED BIRD
Moas, the giant birds of New Zealand (p. 25), show what might have happened in a world without mammals—birds could have become dominant. Early in the Tertiary period, when mammals were still all fairly small, birds did, in fact, dominate. Huge flightless predatory birds evolved and preyed on mammals.

EVOLUTIONARY ISLANDS
The separation of the continents affected mammal evolution greatly, with distinctive groups developing in isolated continents.

SABER TOOTH
Large tigerlike predators with massive stabbing teeth evolved to prey on slow-moving, thick-skinned creatures such as mammoths.

Fossil Miocene leaves

ADVANCED LEAF
These leaves, which are about 20 million years old, are from a flowering plant, the most recent plant form to evolve. These only appeared during the Cretaceous. Until then the dominant plants were the conifers and cycads.

TERTIARY PERIOD

CENOZOIC ERA

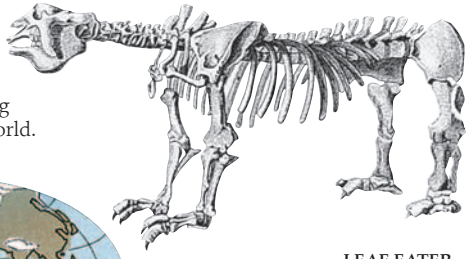
Artist's impression of *Glyptodon*

ARMORED ANIMAL
The *glyptodon*, one of South America's many unique mammal species, is now extinct. After a long interval as an island, South America was reunited with North America by a fall in sea level. Competition, or predation, by invaders from the north forced many South American mammals into extinction.

Bony plates of *Glyptodon*

CLEVER NEANDERTHALS
The skull of Neanderthals suggests a brain at least as large as that of modern humans. The image of Neanderthals as dim and brutish is based on a mistaken 19th-century study of a skeleton. However, they were very strong and stocky and seem to have been well suited to the Ice Age climate.

THE MODERN WORLD
By the Quaternary, the continents had almost reached their present positions. Their slow movement about the globe is still continuing, however, and this produces earthquakes in some places, such as California. Ice ages and rapidly fluctuating climates have been an important factor in evolution during the Quaternary period, cooling the climate all over the world.



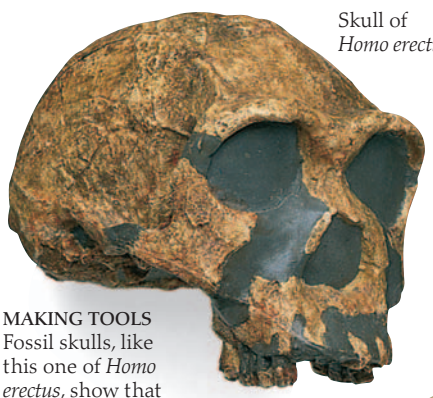
LEAF EATER
Megatherium, the giant ground sloth of South America, probably fed by sitting on its haunches and pulling down tree branches or whole trees to eat the leaves.

QUATERNARY PERIOD

CENOZOIC ERA

Human evolution

The fossil record gives a clear picture of how upright-walking, large-brained creatures called hominids evolved from an apelike ancestor. Fossil remains have been found of some 20 human-related species that have lived and died out over the last 6 million years since humans and chimps diverged. Few are represented by complete skeletons but they do indicate that small apelike human relatives walked upright at least 4 million years ago before there was any significant increase in brain size, which happened around 2.5 million years ago. The first members of our species (*Homo sapiens*) appeared in Africa some 200,000 years ago.



Skull of *Homo erectus*

Flint hand ax from 200,000 years ago

MAKING TOOLS
Fossil skulls, like this one of *Homo erectus*, show that the human brain gradually grew larger, beginning about 2.5 million years ago. At the same time, the ridges above the eyes became smaller, and the face and jaw began to jut out less. Increasing intelligence and the ability to make better tools apparently went together. The earliest stone tools, made in Africa about 2.5 million years ago, were simpler than the hand ax shown here.

Modern human skull

BIGGER BRAINS
Increasing intelligence undoubtedly contributed to the survival of early hominids. For example, *Homo erectus* cooperated to hunt large animals, and this would have required speech and intelligence. But the very great intelligence and creativity of modern humans seem to go beyond what might have aided survival in the wild. It is difficult to see musical gifts or mathematical abilities as a result of natural selection. Some human behavior, good and bad, actually runs contrary to natural selection.

Mozart, the musical child prodigy

Classifying life

TAXONOMY—THE SCIENCE OF CLASSIFYING ORGANISMS, both living and fossil—began with the work of Carl Linnaeus in the 18th century. Linnaeus set up a hierarchy of categories for grouping organisms with similar physical characteristics. Cladistics, or phylogenetics, is an alternative system developed in the 1950s and 1960s. It uses genetics, as well as physical characteristics, to sort organisms into groups called clades. From these, "family trees" are constructed to show the evolutionary development of species and the relationships between them.

CARL LINNAEUS

Linnaeus (1707–1778) was a Swedish botanist who studied and lectured at Uppsala University. Often referred to as the "father of taxonomy," he spent much of his life collecting, classifying, and naming plants and animals. In 1735, Linnaeus published the first edition of *Systema Naturae*, his classification of living organisms. Linnaeus's system—and his method of naming organisms—remains in use today.

Illustration from *Systema Naturae*

Fossil skull of *Homo habilis*

NAMING ORGANISMS

Linnaeus adopted Latin as the language of taxonomy. He gave each species a unique two-word name, or binomial, by combining its Latin genus and species names. For example, *Homo sapiens* is the binomial for modern humans. What makes the name unique is the species part. Extinct humans also carry the generic name *Homo*, such as *Homo habilis* ("handy man"), but only modern humans are referred to as *Homo sapiens* ("knowing man").

WHAT IS A SPECIES?

The basic unit of classification is the species. This is defined as a group of similar individuals that are capable of breeding together in the wild to produce fertile offspring (as opposed to infertile hybrids). For example, the Indian rhinoceros (*Rhinoceros unicornis*) cannot breed successfuly with any other of the five rhinoceros species, including the Javan rhinoceros (*Rhinoceros sondaicus*), the other one-horned species.

Indian rhinoceroses

LINNAEAN CLASSIFICATION

The kingdom, the largest grouping, is at the top of Linnaeus's classification hierarchy. There are five kingdoms, which separate living things into plants, fungi, animals, bacteria, and proctoctists. Each kingdom is divided into ever smaller categories. The smaller the category, the fewer the organisms in it and the more features they have in common. At the bottom of the hierarchy is the species—the most exclusive unit of classification, containing just one organism. The chart below shows the classification of the Indian rhinoceros.

KINGDOM: ANIMALIA
(Animals: 35 phyla).
The kingdom Animalia contains organisms that take food into their bodies and that develop from embryos.

PHYLUM: CHORDATA
(Chordates: 12 classes)
All animals in this phylum have a notocord—a precursor of the backbone—at some point in their lives.

CLASS: MAMMALIA
(Mammals: 28 orders)
Grouped in the class Mammalia are all animals that possess a single jawbone, fur, and mammary (milk-producing) glands.

ORDER: PERISSODACTYLA
(Odd-toed hoofed mammals: 3 families)
This is a group of plant-eating mammals that walk on odd-numbered toes. It includes horses, zebras, tapirs, and rhinoceroses.

FAMILY: RHINOCEROTIDAE
(Rhinoceroses: 5 genera)
This family within the Perissodactyla order contains the rhinoceroses—odd-toed hoofed mammals with horns on their noses.

GENUS: *RHINOCEROS*
(One-horned rhinoceroses: 2 species)
The genus *Rhinoceros* is made up of the one-horned rhinoceroses—the Indian and Javan rhinoceroses.

SPECIES: *UNICORNIS*
(Indian rhinoceros)
Found in Nepal, Bhutan, and India, this rhinoceros cannot breed with the smaller Javan rhinoceros, the other member of its genus.

Sharks

Amphibians

In cladistics, groupings work differently from those used in Linnaean classification, which is why crocodiles but not other reptiles are shown in this diagram

Crocodiles

Birds

Mammals

Ray-finned fish

Crocodiles are featherless

Flight feathers—feathers that are adapted for flight (dinosaurs had nonflight feathers)

Mammals have one pair of holes behind the eyes

Amphibians branch off, since their eggs are not waterproof

Postorbital skull openings—two pairs of holes in the skull behind the eye

Amniotic egg—a waterproof membrane around a developing embryo

These fish have fins made of spines and skin, rather than muscular limbs

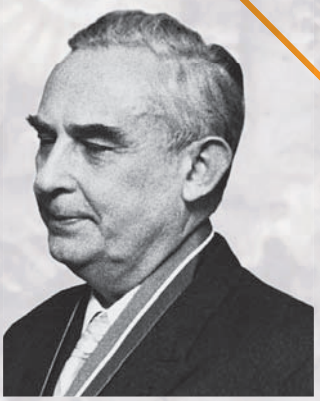
Four limbs—muscular limbs characterize the tetrapods

Sharks branch off, since their vertebral column is made of cartilage, not bone

Bony skeleton—vertebral column and other parts of skeleton made of bone

Common ancestor

Vertebral column—a jointed and flexible rod of bone or cartilage from head to tail



WILLI HENNIG

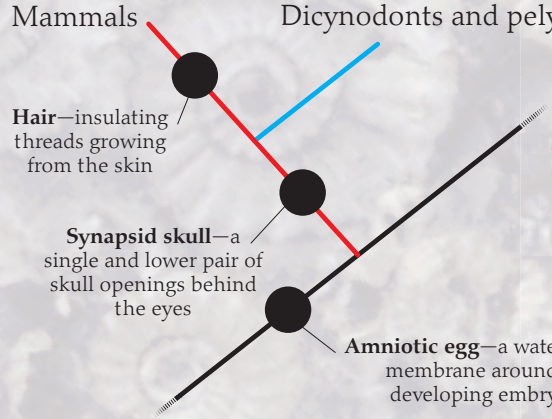
Cladistics was founded by the German biologist Willi Hennig (1913–1976). An expert on flies and mosquitoes, Hennig published his most influential work, *A Basic Outline of a Theory of Phylogenetic Systematics*, in 1950.

CLADISTICS FAMILY TREE

The diagram above shows a group of organisms descended from a common ancestor. This type diagram is known as a cladogram, or phylogeny. The animals in the diagram are part of the chordate clade—the vertebrates. They are all related to the first vertebrate, which appeared around 540 million years ago. The branching patterns are the result of evolution. Each new characteristic that evolves over time, indicated by a black dot, produces a point of divergence. The animal group that does not possess this characteristic branches off the main trunk of the diagram.

Cladograms and the fossil record

Thanks to the fossil record, which tells us about the characteristics of extinct organisms, cladograms can be used to show the relationships between living and extinct groups. Here, the mammal line of the main diagram has been amended to include two extinct groups of mammal-like reptiles—dicynodonts and pelycosaurs. Like mammals, they developed in an amniotic egg and had a skull opening behind each eye (in humans this is reduced to an indentation). The development of hair separates the mammals from the dicynodonts and the pelycosaurs.



Dimetrodon, an extinct pelycosaur

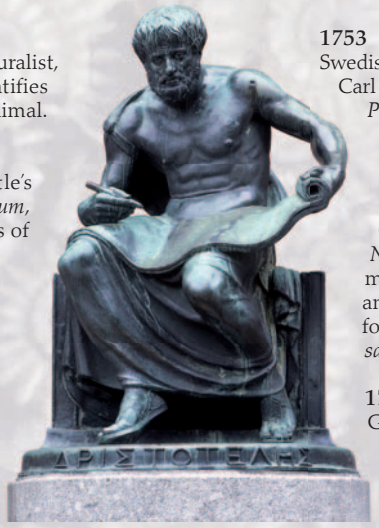
Discoveries in evolution

Our understanding of life and its history has developed since Classical times, when scholars first questioned the nature of plants and animals and their fossil remains. Hundreds of years of discoveries, especially those of the 19th and 20th centuries, increased our knowledge of the abundance, diversity, complexity, and evolution of life. Today, we understand the connections between the molecular and genetic makeup of a single cell and the whole of life and its evolution over 3.5 billion years.

c. 350–340 BCE
Aristotle, the ancient Greek naturalist, closely observes nature. He identifies around 560 different types of animal.

322 BCE
In Greece, Theophrastus, Aristotle's pupil, publishes *Historia Plantarum*, which classifies nearly 500 types of plant, and *De Causis Plantarum*, which explains plant growth.

c. 200 CE
Early Christian philosopher Tertullian asserts that fossils found on mountains were deposited there by the waters of the biblical flood. This idea is known as diluvialism.



Statue of Aristotle

1551
Conrad Gesner, a Swiss physician and naturalist, publishes *Historia Animalium*, a catalog of the then known animals. He follows this in 1565 with *De Rerum Fossilium* ("On Things Dug Out of the Earth"), which is one of the first illustrated catalogs of fossils.

1673
Antoni van Leeuwenhoek, a Dutch draper and amateur naturalist, uses a microscope to reveal details of animal and plant cells for the first time. His microscope can magnify objects 250 times.

1694
Rudolph Jakob Camerarius, a German professor of physics at the University of Tubingen, publishes his *Epistola de Sexu Plantarium*. He includes experimental evidence to show that plants reproduce sexually with the deposit of male pollen on the female stigma.

Hibiscus rosa-sinensis flower, showing a long stigma

1753
Swedish naturalist and botanist Carl Linnaeus publishes *Species Plantarum*, which forms the basis of the modern classification of plants.

1758
Carl Linnaeus's book *Systema Naturae* forms the basis of the modern classification of animals. Modern humans are formally classified as *Homo sapiens* for the first time.

1796
Georges Cuvier, a French naturalist and anatomist, analyzes the skeletal structure of the extinct *Megatherium* from an illustration and concludes that it had been a giant ground sloth. Cuvier's work shows how all vertebrates have a common basic skeletal structure, whose modifications give clues to how each animal lives.


Fossilized claw of *Megatherium*

1801
American showman Charles Wilson Peale excavates the skeleton of a mastodon, an extinct relative of the elephant.

1802
English clergyman William Paley publishes *Natural Theology, or Evidence of the Existence and Attributes of the Deity*, which views all adaptation in the natural world as evidence of God's handiwork.

1809
The publication of a treatise *Philosophie Zoologie* by French naturalist Jean-Baptiste de Lamarck, gives the first reasoned theory of "transformism," which we now know as evolution.

1822
British doctor and fossil hunter Gideon Mantell discovers teeth from an extinct giant reptile that he names *Iguanodon*.

1826
German biologist Karl Ernst von Baer discovers the egg cells in female mammals. This lays the foundation of modern embryology, describing embryonic development from egg stage to birth.

1830–1833
Charles Lyell, a British geologist, publishes his *Principles of Geology*, which argues that the distant past should be explored only through an understanding of the natural forces operating in the present. This becomes known as the principle of uniformitarianism.

1832–1836
HMS *Beagle* makes a round-the-world survey voyage under Captain Robert Fitzroy, with English naturalist Charles Darwin invited as the expedition's naturalist.

1837
Charles Darwin begins a notebook on the "transmutation" of species.


19th-century dinosaur illustration

1841
British anatomist Richard Owen coins the name dinosaur ("terrible lizard") and publishes the first description of the dinosaurs' defining characteristics.

1844
The anonymously published book *Vestiges of the Natural History of Creation* outlines a theory for the evolution of life from primitive single-celled organisms to more complex, advanced forms such as humans. In 1884, it is finally revealed that the book was written by the Scottish publisher Robert Chambers.

1844
Charles Darwin shows an outline of his theory of evolution to the British botanist Joseph Hooker.

1854
Alfred Wallace, a British naturalist and professional collector, independently comes up with the idea of evolution by natural selection while working in Malaysia and Indonesia.

1858
Charles Darwin and Alfred Wallace produce a short joint paper on evolution by natural selection. Its publication is arranged by Joseph Hooker and Charles Lyell.

1859
Charles Darwin publishes his book *On the Origin of Species*, which outlines his ideas on evolution.

1860
British biologist Thomas Henry Huxley defends Darwin's theory of evolution at the Oxford meeting of the British Association for the Advancement of Science, when it is attacked by the Bishop of Oxford, Samuel Wilberforce.

Model of *Archaeopteryx*

1861
In Germany, a fossil of *Archaeopteryx*, a primitive bird, is found. It has impressions of feathers and a long, bony tail. Huxley realizes that this fossil links birds and reptiles, making it the first good evidence to support Darwin's theory of evolution.

1863
The first extinct human relative (*Homo neanderthalensis*) is described and named by William King, a geology professor in Galway, Ireland. The fossil remains had been found in Germany in 1856, but were not at first thought to be different from modern humans.

1866
Austrian monk Gregor Mendel publishes an account of his experiments with breeding pea plants. He realizes that peas carry "particles" of heredity (now called genes), some of which are more dominant than others.

1866
British physicist William Thomson, later Lord Kelvin, says that Earth is 100 million years old at most—not the many hundreds of millions of years suggested by Darwin and Lyell. In fact, Earth is about 4.5 billion years old—closer to Darwin and Lyell's estimate than Thomson's.

1870s
Ernst Haeckel, a German biologist and naturalist, develops the idea of "evolution as progress," which assumes that all nature is moving toward a final goal: human beings.

1907
American geneticist Thomas Hunt Morgan begins his work on fruit flies. His research will help to show that most characteristics are controlled by many genes (tiny stretches of the molecule DNA).

1930
English mathematician Ronald Fisher publishes *The Genetical Theory of Natural Selection*. It proves that Mendel's ideas on genetics support Darwin's theory of natural selection, rather than oppose it, as was previously thought.

1953
The double-helix structure of the DNA molecule is published by American James Watson and Englishman Francis Crick.

1962
American scientists Linus Pauling and Emile Zuckerkandl develop the idea of the molecular clock. This uses differences in DNA sequences and proteins between species to calculate how long ago two species diverged.

1968
American geneticist Sewell Wright publishes the first volume of his treatise on *Evolution and the Genetics of Populations*. He uses mathematics to link genetics to natural selection, and develops the idea of genetic drift—that random changes can occur in genes by chance, rather than by natural selection.

1968
Japanese geneticist Motoo Kimura proposes his neutral theory of molecular evolution, which states that genetic changes can occur at the molecular level that have no influence on an individual's fitness.

Dolly the cloned sheep, 1996

1996
British biologists Ian Wilmut and Keith Campbell clone (reproduce) a lamb called Dolly from a single adult udder cell of a black-faced ewe. Dolly is an exact genetic copy of that ewe, instead of having inherited her genes from two genetically different parents. Scientists think that cloning can help genetic research, but some people see it as tampering with nature.

The mouse genome was outlined in 2002

2000
The working draft of the international Human Genome Project is published. The project aims to find the makeup of the human genome—the sequence of base pairs that make up human DNA and the 25,000 or so human genes. The project began in 1990, headed by James Watson.

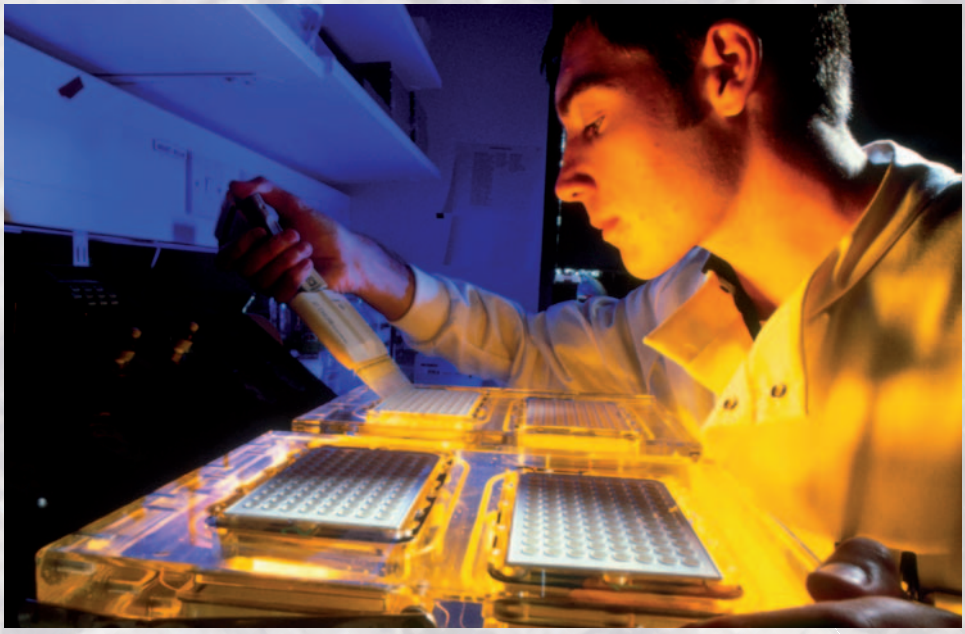
2002
The mouse genome is outlined. Of the mouse's 30,000 or so genes, some 80 percent have direct counterparts in the human genome, and 99 percent show some similarity.

2003
The complete draft of the human genome is published. Further analysis continues.

2005
Publication of the outline of chimp genome, which is only 2.7 percent different from the human genome. These differences, which include certain genes involved in speech development, have evolved over the 6 million years or so since humans and chimps last shared a common ancestor.

2006
The Neanderthal Genome Project is announced by Germany's Max Planck Institute. It is already known that Neanderthal and human DNA is 99.5 percent identical, and that the genomes are roughly the same size. Ancient DNA from a 38,000-year-old male Neanderthal from Croatia is currently being extracted and sequenced to produce an outline of the Neanderthal genome.

Human genome research, 1990 to present



Find out more

THE SCIENTIFIC STUDY OF EVOLUTION is over 150 years old. Since Darwin and Wallace first proposed their theory in 1858, a vast amount has been published by scientists on the subject. Never before has there been so much information available about evolution and related topics such as fossils, natural history, and the protection and conservation of wildlife. You can find facts, figures, and stories in public libraries and on the internet, get a feel for the stunning variety of animal life at a zoo, and encounter the creatures of the past in a museum. You can also get involved by joining a conservation group or taking up a nature hobby.

Field Museum, Chicago, Illinois

Meeting the animals at Singapore Zoo

ZOOS AND BOTANICAL GARDENS

The world's major zoos and botanical gardens allow us to appreciate life's diversity and abundance and get close to the extraordinary animals and plants that populate our planet. Today, zoos and botanical gardens also play a vital role in the conservation of rare and endangered species, reminding us of how we relate to and affect the natural world around us.

USEFUL WEBSITES

- Understanding Evolution, a website from the Museum of Paleontology, California, is an excellent in-depth interactive site on evolution: **http://evolution.berkeley.edu**
- The American Museum of Natural History has an outstanding natural history and evolution site; its "Ology" section is specially for kids: **www.amnh.org**
- The website of the Smithsonian Institution has an "Explore a topic" link with resources on subjects such as "The Evolving Earth" and "The Diversity of Life": **www.mnh.si.edu**
- Based on the PBS miniseries Evolution, this website is one of the most comprehensive evolutionary science sites on the internet, with FAQs, online activities, and more: **http://www.pbs.org/wqbh/evolution/**
- The first website dedicated entirely to the life and tmes of Charles Darwin features detailed maps of the Beagle voyage: **www.aboutdarwin.com**
- The World Wildlife Fund's website has databases, photo galleries, video clips, images from camera traps, games, and more: **www.wwf.org**
- The National Audubon Society's kids' section includes bird-themed games and suggestions for how you can help protect birds: **www.audubon.org/educate/kids/**
- The IUCN's Red List (see opposite) has a searchable website with information on species facing a high risk of global extinction: **www.iucnredlist.org**

VISIT A MUSEUM

A visit to a natural history museum is a great way to get a good overview of the development of life on Earth, and the weird and wonderful species that populated the planet in past ages. Many museums have interactive displays and some exhibit spectacular dinosaur skeletons. Most museums maintain their own websites that give opening times and background information on the objects in their collections.

NATURE HOBBIES
From childhood, Charles Darwin was an avid collector of bugs. A hands-on nature hobby, such as bird-watching, bug hunting, or plant identification, is still a fun way of getting to know how nature works. Taking photos and making notes and drawings will help you learn to identify different species. If you do collect animal specimens, make sure you return them to their natural habitats. Even plants should be observed rather than picked.

Using a net is an easy way to catch flying insects, but they should always be released again once you have studied them

Places to visit

AMERICAN MUSEUM OF NATURAL HISTORY, NEW YORK CITY
The museum has the world's single largest collection of dinosaur fossils, with over 100 specimens on show. Pay them a visit at night, on one of the museum's sleepovers!

THE FIELD MUSEUM, CHICAGO, ILLINOIS
The Evolving Planet exhibit at this world-class museum takes visitors on a four-billion-year tour of life on Earth.

PAGE MUSEUM AT THE LA BREA TAR PITS, LOS ANGELES, CALIFORNIA
On the site of the famous tar pits, you can see the remains of many extinct animals that got stuck there.

DINOSAUR VALLEY STATE PARK, GLEN ROSE, TEXAS
In the streambed of the Paluxy River, you can take a look at some of the best-preserved dinosaur footprints in the world.

Conservation work on a reed bed

LOCAL CONSERVATION GROUPS
Every region has its own natural history heritage. There is now a growing appreciation of how valuable, and how fragile, this heritage is. Many conservation groups work to protect local wildlife and its habitats, and the fossil sites that tell us about life in the past. Most groups organize days when you can take an active part in conservation by helping with tasks such as clearing scrub, replanting, and so on. Public libraries and web-based searches can provide names and addresses of local groups.

COLLECTING FOSSILS
Fossils provide important and fascinating evidence for evolution. Fossil collecting is a hobby that can be enjoyed by anyone, but it is essential to check whether it is legal to collect from a particular site, since many countries have strict rules about collecting and you may need a license. Always make sure you are supervised by an adult when you are fossil collecting, and use the correct equipment, such as rock hammers, safety helmets, goggles, and gloves. Never collect below cliffs or anywhere there might be rockfalls.

INTERNATIONAL CONSERVATION
Your school class could fund-raise and campaign for international organizations like the World Wildlife Fund, which promotes the cause of wildlife conservation worldwide. The International Union for the Conservation of Nature (IUCN) is a global body that works to find solutions to problems that put species at risk. Its Red List gives the current status of plant and animal species that are threatened with extinction. It is updated regularly.

Conservation workers help a cheetah in Africa

Glossary

ACQUIRED CHARACTERISTICS The noninheritable characteristics acquired by an organism in its lifetime. Large muscles produced by weight-lifting are acquired characteristics.

ADAPTATION The process of modification by natural selection that makes an organism more able to survive and reproduce in its environment. Also, any characteristic produced by this process.

ALLELE One of two or more alternative forms of the same gene.

AMINO ACID One of a group of 20 carbon-based molecules that form the building blocks of thousands of different proteins in living things.

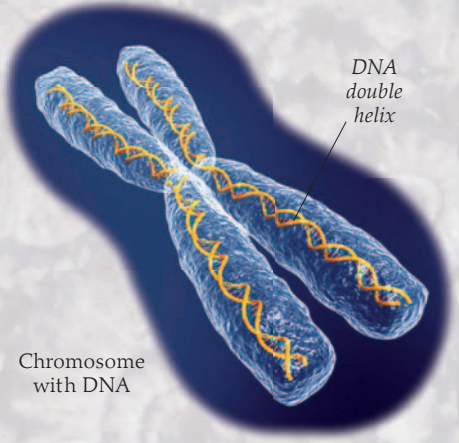
ARTIFICIAL SELECTION The alteration of a population of plants or animals by selective breeding carried out by humans. Dog breeds, for example, are produced by artificial selection.

BASE A chemical compound that forms part of a DNA molecule. Bases form the "rungs" of the molecule's ladderlike structure, with two bases (a base pair) per rung.

BINOMIAL The two-word scientific name of an organism, made up of its Latin genus and species names. The binomial of modern humans, for example, is *Homo sapiens*.

CAMBRIAN EXPLOSION The emergence of many new and complex life forms in the Cambrian Period (542–488 million years ago).

CATASTROPHE THEORY The 19th-century idea that the change in fossils from rocks of one geological period to the next could be explained by global catastrophes such as great floods, powerful earthquakes, or changes in climate.



CELL A tiny unit of living matter. Cells are the building blocks of all living things. The control center of a cell is the nucleus.

CHROMOSOMES Threadlike DNA packages found in the cell nucleus. They carry genes and all the information needed to make a cell work.

CLADISTICS A method of classification in which members of a group, or clade, share a more recent common ancestor with one another than with members of any other group. Cladistics is also known as phylogenetics.

CLADOGRAM A branching diagram, or phylogeny, showing the evolutionary history and interrelationship of species.

CLONE To produce a genetic replica of a cell or organism; also, the replica itself. Cloning occurs in organisms that reproduce from a single parent (asexual reproduction). Scientists have succeeded in cloning organisms artificially in the laboratory.

COMMON ANCESTOR An ancestral species shared by two or more species. Modern humans and chimps share a common ancestor that lived at least six million years ago.

COMPETITION The struggle between organisms for limited resources, leading to natural selection.

DARWINISM The original theory proposed by Darwin that species evolve from other species by natural selection. Neo-Darwinism is modified by the addition of Mendelism, of which Darwin was not aware.

DILUVIALISM The mistaken idea that all rock strata and fossils were laid down at the same time by catastrophic flooding.

DINOSAURS An extinct group of land-dwelling reptiles that lived in the Mesozoic Era (251–65 million years ago).

DNA Short for deoxyribonucleic acid, which is present in every cell and which gives the hereditary characteristics to a parent organism.

DOMINANT GENE A gene (allele) that shows itself in a living organism's phenotype, or physical form. In humans, the gene for brown eyes is dominant over the gene for blue eyes.

DOUBLE HELIX The coiled, twisted ladder shape of the DNA molecule.

EMBRYO An unborn living organism at an early stage of development.

ENZYME A protein that speeds up and regulates chemical reactions.

EVOLUTION Changes in the genetics and forms of organisms over time.

EXTINCTION The natural dying out of species.

FOSSIL The preserved trace of a once-living organism. Fossils are usually bodily remains (bones, teeth, or shells), footprints, dung, or the impressions of body features.

FOSSILIZATION The way that the buried remains of organisms are preserved when the sediment around them is transformed into rock.

GENE A stretch of DNA that carries instructions to make a particular protein. Genes are the basic units of heredity, which are passed on to the next generation.


Euoplocephalus dinosaur

GENETIC CODE The arrangement of bases in a DNA molecule. The genetic code tells a cell how to convert the sequence of bases into a sequence of amino acids, from which proteins can be built.

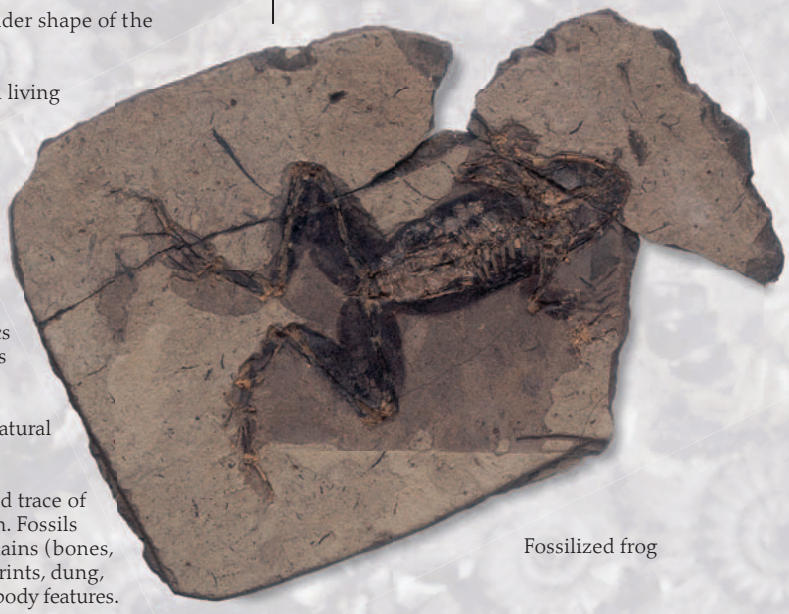
GENETIC DRIFT Randomly occurring changes in the genetic makeup of a population, occurring at the molecular level, rather than by selection.

GENOME All the DNA in a cell or organism.

GENOTYPE The genetic information that an organism inherits from its parents. The genotype interacts with the environment to produce the organism's phenotype.

GENUS A category of classification containing one or more closely related species.

GEOLOGICAL PERIOD A unit of time represented by a sequence of rock strata and their characteristic fossils. Geological periods are subdivided into epochs and stages, and grouped into eras.


Fossilized frog

Mule—a hybrid of a donkey and a horse

HEREDITY The genetic link between successive generations of living organisms.

HOMINID One of a group of upright-walking, large-brained mammals that evolved from apelike ancestors. Humans are hominids.

HYBRID The offspring of a cross between two separate but related species. Hybrids are infertile and cannot reproduce.

ICE AGE An extremely cold period in Earth's history when the ice sheets were much larger than they are today.

INHERITANCE The passing on of characteristics from generation to generation.

INTERBREEDING Sexual reproduction between organisms that involves the exchange of reproductive cells and their DNA.

Invertebrate worm

INTERMEDIATE A living or fossil species that represents an "in-between" stage or link in the evolution of a new group from an existing one.

INVERTEBRATE An animal lacking a backbone.

ISOLATING MECHANISM Scents, sounds, colors, and behavioral signals used by a species to recognize its own kind for breeding.

LAMARCKISM A mistaken theory proposed by Jean-Baptiste Lamarck that an individual can inherit characteristics acquired by its parents during their lifetime.

LOCUS The position of particular gene on a chromosome.

MASS EXTINCTION Rare, relatively brief catastrophic events that cause a significant percentage of organisms on Earth to die out.

MENDELISM The rules governing the way that individual characteristics are passed from parent organisms to their offspring via dominant, recessive, and sex-linked genes.

MIGRATION The movement of organisms from one place to another, either as individuals, groups, or whole populations. If this results in the organisms becoming isolated from the rest of their species, they may eventually evolve into a new species.

MOLECULE A tiny particle of a chemical substance. Molecules are made up of even smaller particles called atoms.

MUTATION A change in a cell's genetic material. If a mutation occurs in a reproductive cell, it can be passed on from one generation to another.

NATURAL SELECTION The process by which organisms that are poorly suited to their environment are slowly weeded out because they fail to survive. Those that are fitter and well adapted to their environment survive better, and produce more offspring. As a result, they pass on their genes to future generations.

NATURAL THEOLOGY The idea that the adaptation of organisms to their surroundings is evidence of design by a creator God.

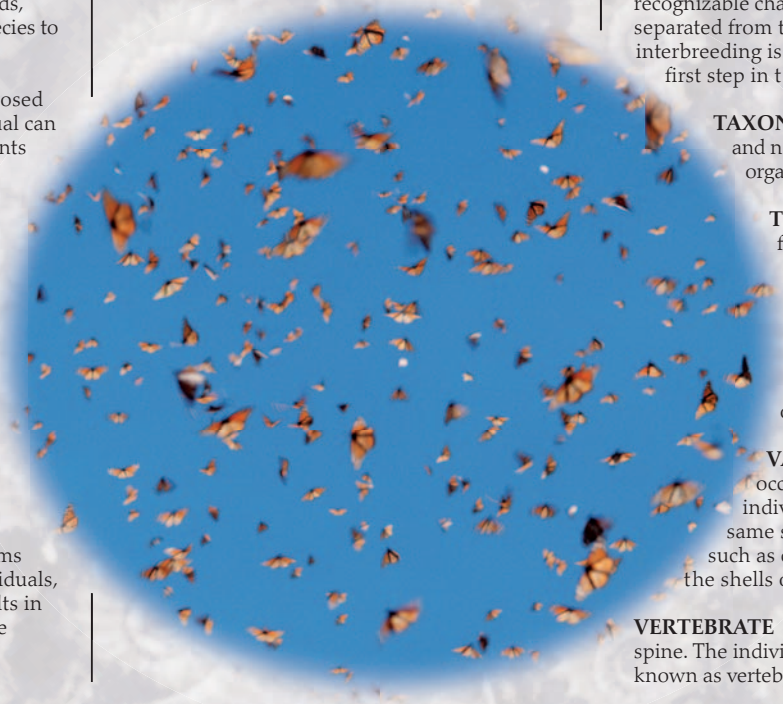
PHENOTYPE The physical characteristics of an organism that result from the interaction between its genotype and the environment.

PLATE TECTONICS The slow movement of the solid rocky plates of Earth's outer layer, or crust, as new seafloor rocks are generated and older seafloor rocks are recycled.

PROTEIN A chainlike molecule made up of amino acids. Proteins form the organic (carbon-based) compounds that are characteristic of living things.

RECAPITULATION The mistaken 19th-century idea that as an embryo develops it goes through all the evolutionary stages of its ancestors.

Migrating monarch butterflies



RECESSIVE GENE A gene (allele) that is hidden when it is partnered by a dominant gene. It only shows in the phenotype if it is partnered by an identical recessive gene. In humans, the gene for red hair is recessive.

RNA (Ribonucleic acid) RNA is a molecule similar to DNA. It is present in all organisms and translates the genetic code into proteins.

SEDIMENTARY ROCK A type of rock formed from the debris of other rocks and sometimes the remains of living organisms.

SEXUAL SELECTION A type of selection in which individuals are favored (selected) over others of the same sex because of their mating behavior. Examples include males fighting for access to females, and females choosing males on the basis of their courtship displays.

Courtship display in ducks

SPECIES A group of organisms that can breed together in the wild. Also a basic unit of classification, referred to by its Latin binomial.

SPONTANEOUS GENERATION The false notion that new microorganisms spontaneously arise from nonliving matter, such as wet straw.

SUBSPECIES A group within a species that has recognizable characteristics, often geographically separated from the rest of the species so that interbreeding is not possible. This is often the first step in the formation of a new species.

TAXONOMY The science of classifying and naming living and extinct organisms.

TETRAPOD An vertebrate with four limbs, or an animal that has evolved from one.

UNIFORMITARIANISM The 19th-century idea that the past can be understood only in relation to the natural forces operating in the present.

VARIATION The naturally occurring differences between individuals and populations of the same species that have a genetic basis, such as color and pattern variations on the shells of seashore mollusks.

VERTEBRATE An animal with a backbone, or spine. The individual bones of the spine are known as vertebrae.

Index

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