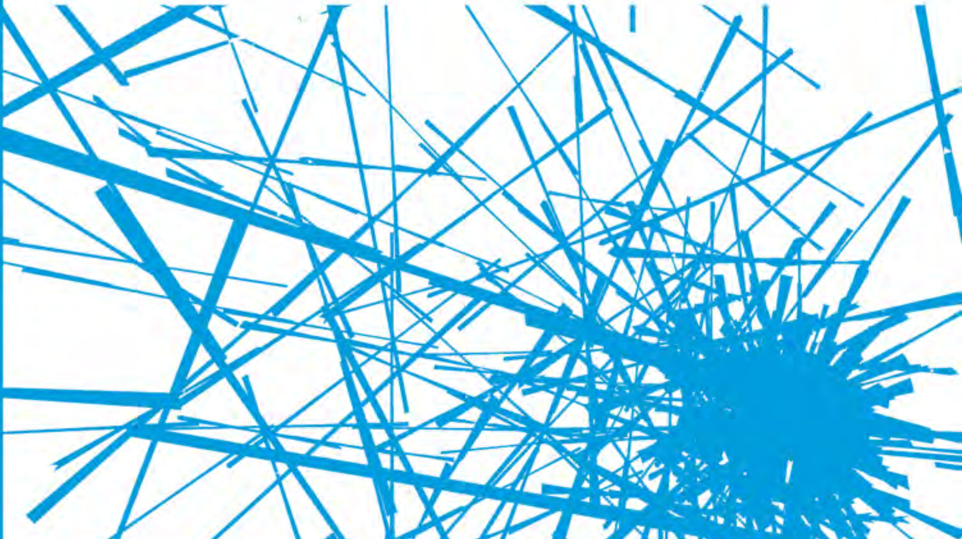
Learning to Solve Problems

A Handbook for Designing Problem-Solving Learning Environments



David H. Jonassen

Learning to Solve Problems

This book provides a comprehensive, up-to-date look at problem-solving research and practice over the last fifteen years. The first chapter describes differences in types of problems, individual differences among problem solvers, as well as the domain and context within which a problem is being solved. Part I describes six kinds of problems and the methods required to solve them. Part II goes beyond traditional discussions of case design and introduces seven different purposes or functions of cases, the building blocks of problem-solving learning environments. It also describes methods for constructing cases to support problem solving. Part III introduces a number of cognitive skills required for studying cases and solving problems. Finally, Part IV describes several methods for assessing problem solving. Key features include the following:

Teaching Focus—The book is not merely a review of research. It also provides specific research-based advice on how to design problem-solving learning environments.

Illustrative Cases—A rich array of cases illustrates how to build problem-solving learning environments. Part II introduces seven different functions of cases and also describes the parameters of a case.

Chapter Integration—Key theories and concepts are addressed across chapters and links to other chapters are made explicit. The idea is to show how different kinds of problems, cases, skills, and assessments are integrated.

Author Expertise—A prolific researcher and writer, the author has been researching and publishing books and articles on learning to solve problems for the past fifteen years.

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A Handbook for Designing Problem-Solving Learning Environments

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To my father, who always claimed that I was a late bloomer. Would that he were here to witness the blossom.

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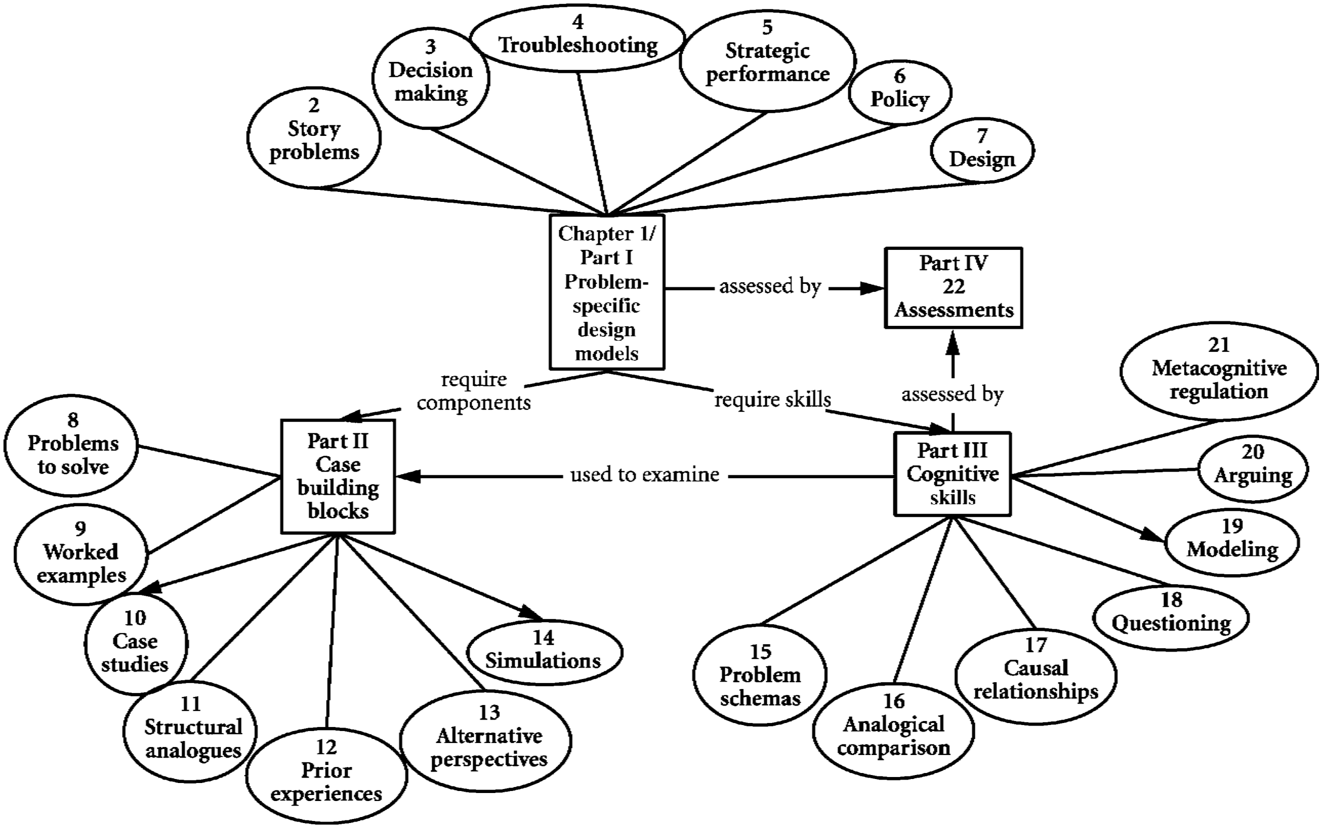
READ ME FIRST

Learning to Solve Problems: A Handbook for Designing Problem-Solving Learning Environments is just that, a handbook. As such, it is a reference source that may be used in a large number of ways to meet many different needs. It is not a novel and so will not make as much sense if read cover-to-cover.

So let me describe how the book is organized. It is divided primarily into three parts. In Part I, I describe different kinds of problems to solve. In order to learn how to solve the different kinds of problems described in Part I, students must examine and analyze a variety of case types that are described in Part II. In order to learn how to solve the different kinds of problems described in Part I, students must engage in the cognitive skills described in Part III. Those skills are used to examine the different cases described in Part II. Part IV contains a single chapter describing numerous methods for assessing how to solve the different kinds of problems in Part I and the cognitive strategies in Part III. Figure 00x.1 illustrates the conceptual interconnectedness of ideas in this handbook.

How should you access the book? That depends on the purpose you have for using the book. You probably have experienced problems and want to know more about them, so you may want to examine different kinds of problems described in Part I. If you are researching specific attributes of problem solving, then you may want to access relevant chapters in Part III. If you are designing problem-solving learning environments (PSLEs), then you want to examine the chapters in Parts II and III. However you use it, I hope that it fulfills some of your needs.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ORGANIZATION OF *LEARNING TO SOLVE PROBLEMS: A HANDBOOK FOR DESIGNING PROBLEM-SOLVING LEARNING ENVIRONMENTS*

Chapter 1 How Does Problem Solving Vary?

Part I: Problem-Specific Design Models

These six chapters describe the different kinds of problems introduced in Chapter 1 as well as the different kinds of cases described in Part II and cognitive supports described in Part III that are necessary for learning how to solve each kind of problem.

Chapter 2 Story Problems
Chapter 3 Decision-Making Problems
Chapter 4 Troubleshooting and Diagnosis Problems
Chapter 5 Strategic-Performance Problems
Chapter 6 Policy-Analysis Problems
Chapter 7 Design Problem Solving

Part II: Cases: The Building Blocks of Problem-Solving Learning Environments

Each chapter in Part II describes a different function that cases can play. These cases are the building blocks for learning how to solve the different kinds of problems described in Part I.

Chapter 8 Cases as Problems to Solve
Chapter 9 Cases as Worked Examples of Well-Structured Problems
Chapter 10 Case Studies: Examples of Ill-Structured Problems
Chapter 11 Cases as Analogies
Chapter 12 Cases as Prior Experiences
Chapter 13 Cases as Alternative Perspectives
Chapter 14 Cases as Simulations

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Each chapter in Part III describes different cognitive skills that are required to learn how to solve the different kinds of problems described in Part I.

Chapter 15 Defining the Problem: Problem Schemas
Chapter 16 Analogically Comparing Problems
Chapter 17 Understanding Causal Relationships in Problems
Chapter 18 Question Strategies for Supporting Problem Solving
Chapter 19 Modeling Problems

Chapter 20 Arguing to Learn to Solve Problems
Chapter 21 Metacognitive Regulation of Problem Solving

Part IV: Assessing Problem Solving

This final chapter describes alternative methods for assessing the ability to solve the different kinds of problems described in Part I.

Chapter 22 Assessing Problem Solving

PREFACE

WHAT IS THIS BOOK ABOUT?

I argue that the only legitimate cognitive goal of education (formal, informal, or other) in every educational context (public schools, universities and [especially] corporate training) is problem solving. I support this claim with five warrants.

First, problem solving is the most authentic and therefore the most relevant learning activity that students can engage in. Karl Popper (1999) wrote a book of essays that claimed that all life is problem solving. In everyday contexts including work and personal lives, people solve problems constantly. No one in personal and professional contexts is rewarded solely for memorizing information and completing examinations. Problem solving is an essential twenty-first century skill, specifically the ability to solve different kinds of non-familiar problems in both conventional and innovative ways and to identify and ask significant questions that clarify various points of view and lead to better solutions (http://www. 21stcenturyskills.org).

Second, research has shown that knowledge constructed in the context of solving problems is better comprehended, retained, and therefore more transferable.

Third, problem solving requires intentional learning. Learners must manifest an intention to understand the system or context in which problems occur in order to solve problems effectively. Meaningful learning cannot occur until and unless learners manifest an intention to learn. All human behavior is goal-driven. The clearer our goals are for learning, the more likely we are to learn meaningfully and mindfully.

Fourth, life is short. Time allocated to learning in every context is always limited. So why not make the most effective use of the time available?

Fifth, knowledge that is recalled and not used in some authentic tasks is too quickly forgotten, cannot be effectively applied, and in most disciplines becomes obsolete in a short time. Therefore, the primary purpose of education should be to engage and support learning to solve problems.

HOW IS THIS BOOK ORGANIZED?

This is a handbook, not a novel, meaning that it is best used as a resource rather than a book to be read from front to back. It is highly integrated and interdependent and not very sequential at all. In each chapter, there are multiple references to descriptions of ideas in other chapters (see Figure 0x.1). Those cross-references are meant to convey the interconnected nature of the ideas about problems solving. This handbook would be a much more effective hypertext than it is a linear text. However, print books are linear, so let me briefly explain how this one is organized.

Chapter 1 summarizes my conception of problem solving, which diverges from traditional phase models of problem solving. Those models conceived of problem solving a process that can be generalized to most if not all problems. I argue in Chapter 1 that problems vary in different ways, so different kinds of problems call on different conceptions and skills. Chapter 1 is probably a good place to start.

Based on those differences among problems, in Part I, I describe different kinds of problems, including story problems, decision-making problems, troubleshooting, strategic performance problems, policy-analysis problems, and design problems. In other work, I have also described algorithmic problems (which many scholars do not regard as problems), rule-using/rule induction problems, and dilemmas. I have not explicated those because of a lack of theoretical and empirical foundation. The point is that there exist different kinds of problems, which call on different skills, so that learning methods should also vary. In Figure 0x.1, note the number of conceptual connections for each kind of problem to the chapters in other parts of the book.

Part II of this handbook describes the building blocks of problem-solving learning environments (a term that represents problem-solving instruction in a more open-ended way than problem-based learning). Cases are the building blocks of problem-solving learning environments

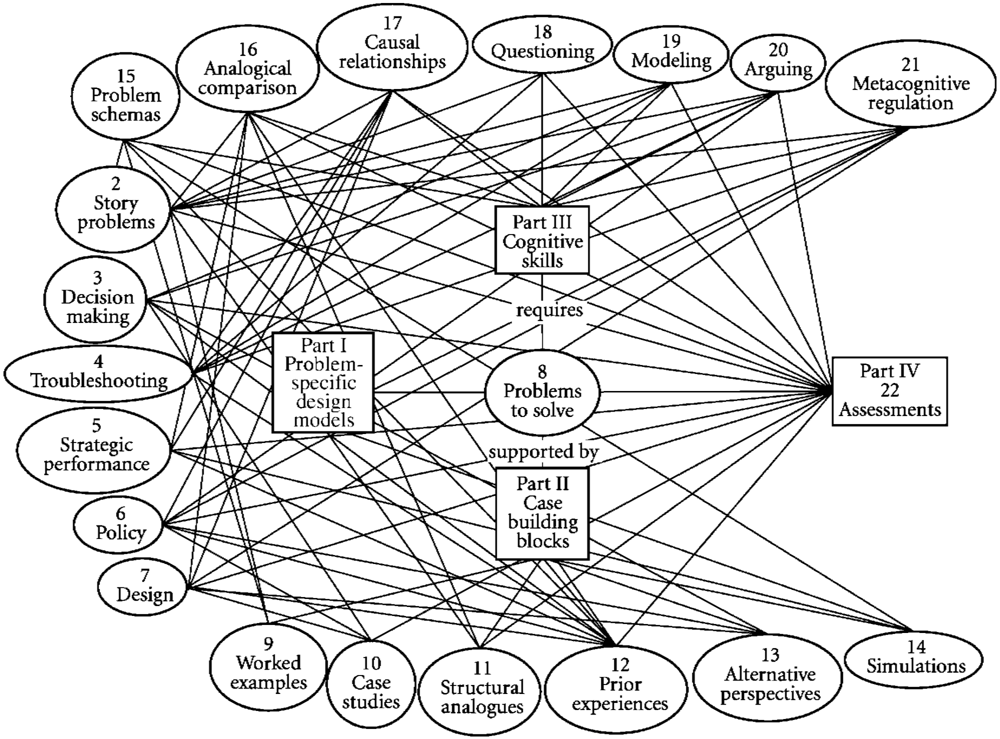
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Figure 0x.1

(PSLEs). In Part II, I describe the intellectual functions of cases and how they support different kinds of problem solving.

In Part III, I describe the cognitive skills that are required to solve problems and how they can be included in PSLEs. The practice and transfer of these cognitive skills form the bases form cognitive strategies that can be applied to problems and regulated by metacognitive strategies (Chapter 21).

Finally, the single chapter in Part IV describes numerous methods for assessing problem-solving ability and the cognitive skills that are required to solve problems. Assessing problem solving can be just as vexing a design problem as engaging and supporting problem solving.

WHAT IS THIS BOOK NOT ABOUT?

This book is not about problem-based learning, per se. Problem-based learning (PBL) is an instructional strategy begun in medical schools around the world and described in greater depth in Chapter 8 and Hung, Jonassen, and Liu (2008).

Rather than PBL methodologies, this book is about how to learn to solve different kinds of problems. Based on psychological and educational literature associated with problem solving, it describes the building blocks and processes for constructing problem-solving learning environments (PSLEs). I chose this term to distinguish the more generic conception of problem solving described in this book from PBL. Most implementations of PBL would probably profit from some of the recommendations described in this book, because we are all fostering the ability of learners to solve problems.

WHAT ARE MY ASSUMPTIONS?

Problem solving is a complex process. The most common historical models of problem solving (e. g., Simon, 1957) employ a means-ends conception of problem solving. That generic theory for solving all problems requires the problem solver to identify the goal state, the current state, and then to deduce the process for moving from the current state to the goal state. The Gestalt psychologist, Wolfgang Kohler, wrote a book on problem solving, *The Mentality of Apes* (1917). Kohler would pose problems to his apes, such as how to retrieve bananas that were out of reach. The apes would stack wooden crates to get closer to the bananas or they might use sticks to reach the prize. Humans (and apes) are obviously capable of conducting means-ends problem solving, however means-ends analysis is unreliable and not often transferable. Therefore, my theoretical assumptions about learning to solve problems include the following.

Problem solving is a schema-based activity. That is, in order to solve problems, learners must construct schemas for problems (see Chapter 15). Constructing models of problems (see Chapter 19) greatly facilitates schema development. Having constructed a robust schema for different kinds of problems, learners are better able to transfer their problem-solving skills.

Learning to solve problems requires practice in solving problems, not learning about problem solving. Problem-solving learning environments (PSLEs) assume that learners must engage with problems and attempt to construct schemas of problems (Chapter 15), learn about their complexity, and mentally wrestle with alternative solutions. Most instruction in schools and universities is about topics. We teach students about sociology, psychology, history, biology, etc. Too seldom do we teach students how to be a sociologist, psychologist, historian, or biologist, which means how to solve problems that emerge from their discipline but invariably involve issues from other disciplines. Most of this book is about building PSLEs that engage and support students in learning how to solve problems by practicing solving problems.

WHAT PERSPECTIVES ARE MISSING?

Because each of us has developed different mental models for problem solving and different scripts for problem-solving instruction, many of you may wonder why I did not include a chapter on this or that. For instance, many readers will ask why I did not include a chapter on the role of creativity and inspiration in many kinds of problem solving. I have no doubt that creativity and inspiration play significant roles in problem solving. The primary reason is that I do not understand creativity. I know that it exists. I believe that successful artists, musicians, designers, manufacturers, and other problem solvers employ creativity in their efforts, however, creativity is specific to the discipline and media in which people solve problems. I believe that some people are more endowed with creativity than others, but exactly what they are endowed with depends on the nature of the problems they solve. The photographer, Edward Weston, called it "a stronger way of seeing." I would interpret that as a keen sense of visual perception. Other famous instances of creativity, such as Archimedes' bath displacement or Kekule's snake dream, can also be explained via common associative reasoning. Admittedly, the associations were unpredictable and unconscious, but they were cognitive associations nonetheless. Clearly creativity and inspiration play a role in problem solving. I am just not certain how, so I choose not to highlight my ignorance. Others have written extensively about creativity and problem solving (de Bono, 1992; VanGundy, 1988). I refer you to their work.

On a related topic, other readers and many people at talks I have presented around the world have asked why I ignore the role of affect in problem solving. Affective aspects, such as confidence, persistence, self-efficacy, anxiety, stress, fatigue, hormone balance, and other affective attributes, play a significant role in problem solving. For me, those aspects are embedded in the problem-solving context. Rather than embedding motivating adjuncts to instruction, such as those suggested by the ARCS model (Keller, 1983), I have argued throughout this book that engaging students in solving important, meaningful, and authentic problems is affectively engaging and gratifying. I view the world through a highly refractive set of cognitive lenses. There is so much that we do not understand about cognition and learning that I have dedicated myself to that pursuit. I believe that cognition and affect interact in significant ways during problem solving and that cognition and affect, like cognition and creativity, cannot be separated. I encourage others to pursue research on affective dimensions of problem solving. For me, there is so much that we do not know about the cognition of problem solving that I will have a significant intellectual focus for the remainder of my career.

This book also ignores the role of social interactions in problem solving, although there is some discussion in Chapter 12 and we have considered it elsewhere (Jonassen, Lee, Yang, & Laffey, 2005). I have no doubt that social interactions and social co-construction of knowledge play vital roles during problem solving in most contexts. Few problems in the everyday world are solved individually. Rather problem solving is distributed among many people, often playing diverse roles, and the tools and sign systems they use to articulate the problems. However, explicating the various social roles and social interactions that support problem solving constitutes another book, which I will leave to someone more learned than I to write.

In Chapter 1, I describe some of the dimensions of problems solving including the nature of the problem and the context in which it occurs. In addition to these dimensions, Jonassen (2007) identified the nature of the problem solver(s) as another critical dimension. That is, individual cognitive, social, and personality differences necessarily affect the ways that people solve problems. There are many variables, such as field independence, that appear to mediate the cognitive processes of problem solving. This book contains no discussion of learners' capabilities, except for a brief introduction on Chapter 1. I refer you the *Handbook of Individual Differences, Learning and Instruction* (Jonassen & Grabowski, 1993), which contains numerous references to individual differences and problem solving.

The examples provided in this book tend to focus on science learning in higher education. Those examples come from funded research that we have conducted and so know more about. So many readers will no doubt criticize the lack of relevant examples for K-12 classes or classes in the humanities or social sciences. When writing a book, it is impossible to please all of the readers any of the time. It would be impossible to provide the range of examples necessary to do that. So, I must rely on your intelligence as a reader to generalize the methods recommended throughout the book to your discipline and grade level. That will constitute a design problem that you must solve if you hope to use this book for designing PSLEs. Also, I regularly conduct classes and workshops on designing PSLEs.

Finally, throughout this book, I have based recommendations upon beliefs as well as empirically validated principles of learning and instruction. My beliefs are reasonably well informed by experience and research, but there are a great many issues and recommendations reported in this book that have little or no empirical support, not because they are not important issues. Rather, there simply has not been any research conducted on the hundreds or even thousands of issues that are raised in the book. The research base on problem solving is remarkably thin. My intention has been to provide a coherent model of meaningful problem solving; however, some parts of the model are well grounded in evidence, and for others evidence is not yet available. Each chapter raises numerous potential research questions. Throughout the book, there are literally hundreds of possible research studies that need to be conducted. Like most issues in instructional design and technology, there are far more unanswered questions than empirically verified questions. That represents a good-news-bad-news situation for researchers entering the field. While for newer technologies they have few prior results to base research questions on, there are seemingly an infinite number of questions to ask. Contrast that situation with many disciplines, such as English literature, where articulating an original research question is extremely difficult.

Also missing are the perspectives and processes that I am yet to learn about. This book represents my theory of problem solving at the beginning of 2010. Like most theories or mental models, it will grow with new knowledge and perspectives.

HOW SHOULD YOU USE THIS BOOK?

This book is a handbook, meaning that it is best used as a resource rather than a book to be read from front to back. This handbook is replete with cross-references to other chapters. As such, it is intended as a reference source that will need to be criss-crossed (See Chapter 13 for a description) and applied while designing and building PSLEs. Here is one possible model.

Each year, I teach a course entitled "Designing Problem-Solving Learning Environments." Rather than lecturing students about problem solving, I indenture my students to professors on campus who want to implement more problem solving into their courses. For the semester, students work with the professors to articulate the kind of problem solving they expect and then construct a PSLE to engage and support student in relevant, authentic problem solving. In that course, students generally (though not always) conduct the following design activities.

1. Interact with professor to identify and articulate problem or to suggest problems that may be relevant to discipline (see authenticity discussion later).
2. Analyze problem, first by creating a causal model of the problem space (see Chapter 17).
3. Then conduct an activity theory analysis to identify the historical, cultural, experiential factors that affect problem solving on whatever context is chosen (not described in this book; see Jonassen, 2000b; Jonassen & Rohrer-Murphy, 1999).
4. Determine what kind of problem it is.
5. Construct case supports and cognitive scaffolds for each problem type using Table 0x.1. These are recommendations but not all empirically proven. In fact, they provide potential hypotheses for hundreds and hundreds of studies.
6. Construct a PSLE that includes some combination of case components and cognitive strategies.
7. If time permits, implement and assess the effects of the PSLE. This activity is usually accomplished in a subsequent semester and becomes the first round of a design-based research study.

WHAT KINDS OF RESEARCH IS NEEDED ON PROBLEM SOLVING?

Although the primary goal of this book is to help you to design more effective learning environments to different kinds of problems, an

Table 0x.1

Problem Type	Case Components	Cognitive Skills
Story	Problems, worked examples, analogues	Problem schema, analogical, causal, questioning, argumentation, modeling
Decision making	Problem, case studies, prior experiences, alternative perspectives	Causal, argumentation, modeling, mental simulation (scenario construction)
Troubleshooting	Problems, prior experiences	Causal, argumentation, modeling
Strategic performance	Problems, prior experiences, simulations	Problem schema, analogical, causal, mental simulation (scenario construction)
Policy analysis	Problems, case studies, prior experiences, alternative perspectives	Analogical, causal, questioning, argumentation, modeling
Design	Problems, prior experiences, alternative perspectives	Causal, argumentation, modeling

implicit goal is to stimulate research into the factors that determine effective problem solving. Each chapter in this book raises numerous research questions about learning to solve problems. Relative to the importance of problem solving in our lives, there is very little research on most kinds of problems. There are hundreds, if not thousands, of potential research questions embedded in the chapters in all four parts of the book. I sincerely hope that this book will stimulate and support that research.

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To the many students over the years to whom I have attempted to explain this evolving theory of problem solving.

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ABBREVIATIONS

CBR	case-based reasoning
CDM	critical-decision method
DFCS	Decision Function Coding System
GBS	goal-based scenario
ITS	intelligent tutoring system
KITE	Knowledge Innovation for Technology Integration
LSS	Learning Strategies Survey
MAI	Metacognitive Awareness Inventory
MSLQ	Motivated Strategies for Learning Questionnaire
PARI	precursor, action, result, interpretation
PBL	problem-based learning
PSLE	problem-solving learning environment
RPDM	recognition primed decision making
STAPSS	Student Thinking About Problems Solving Scale
TLE	troubleshooting-learning environment

1

HOW DOES PROBLEM SOLVING VARY?

WHAT IS A PROBLEM?

This book is about learning to solve problems, so first I shall describe what a problem is, that is, what is being solved. There are many conceptions of a problem. The word "problem" derives from the Greek *problema*, meaning obstacle. The word "problem," as used in this book, refers to a question or issue that is uncertain and so must be examined and solved. Everyday life and work are filled with uncertain situations for which no resolution is immediately known. What route should I take to work to minimize traffic congestion? How can we afford an addition to the school building? How can we accelerate the collection of receivables? What will be the most effective method for marketing our new product to the target group? How can we increase fatigue strength to this material without increasing cost significantly? Which medical-insurance program should I select? These are all questions about situations that are currently unknown and therefore need resolution. Those problem situations vary from algorithmic math calculations to vexing and complex social problems, such as mitigating violence in the schools. For me, finding or solving the problem must have some social, cultural, or intellectual value. That is, someone believes that the problem is worth solving. "Problems become problems when there is a 'felt need' or difficulty that propels one toward resolution" (Arlin, 1989, p. 230). That is, someone believes that the question is worth answering. If no one perceives a need to answer the question, there is no problem. This latter attribute may eliminate most formal, in-school problems from the category of real problems because students often do not perceive a need to find the unknowns to the types of problems posed in schools. However, because their teachers do perceive such a need, they are normally regarded as problems.

For many people, the concept *problem* has a more affective conotation. For them, a problem is a situation or matter that presents a perceived difficulty. They may have a *problem child*, or I am having a *problem with my boss*. Synonyms for problems include “dilemma,” “quandary,” “obstacle,” “predicament,” and “difficulty,” all of which have heavy affective connotations. Indeed, problems often do represent predicaments, and problems are often difficult. However, for purposes of this book, I regard problem solving as a primarily cognitive activity. Although many problems engage affect, I will not deal explicitly with those issues. The cognitive perspective on problems considers a problem as “a question to be resolved.” That is the spirit in which this book addresses problems. Why? Because we are constantly solving problems in our everyday and professional lives, so educators ought to help students learn to solve the problems they will face in their professional lives and perhaps those that plague their personal lives.

Psychologists have examined problems and problem solving fairly extensively, beginning with information-processing theorists. A problem, from an information-processing perspective, consists of sets of initial states, goals states, and path constraints (Wood, 1983). Solving a problem means finding a path through the problem space that starts with initial states passing along paths that satisfy the path constraints and ends in the goal state. According to Davidson, Deuser, and Sternberg (1994), problems consist of givens (the elements, relations, and conditions that define the initial state), goal (desired solution), and obstacles (characteristics of the problem solver or the problem situation that make it difficult to transform initial state into goal state). Unfortunately this information-processing conception has been used largely to describe well-structured problems (to be described later in this chapter and more extensively in Chapter 2). For most everyday, ill-structured problems (also described later in this chapter), the goal states and path constraints are often unknown or are open to negotiation, and so there are no established routes through path constraints toward the goal state. Information-processing models of problem solving are inadequate for representing the many kinds of problem solving, especially those that engage situated, distributed, and social aspects of problem solving. As problems become more ill defined, their solutions become more socially and culturally mediated (Kramer, 1986; Roth &

McGinn, 1997). What becomes a problem arises from the interaction of participants, activity, and context.

WHAT IS PROBLEM SOLVING?

My assumption in this book is that problem solving is primarily a cognitive process. In the Introduction and earlier in this chapter, I recognize the importance of affect and motivation on problem solving; however, in this book, I focus on the cognition of problem solving.

There have been many cognitive conceptions of problem solving. As alluded to before, a number of information-processing models of problem solving, such as the classic General Problem Solver (Newell & Simon, 1972), have explained problem-solving processes. The General Problem Solver specifies two sets of thinking processes associated with the problem-solving processes, understanding processes and search processes. Another popular problem-solving model, the IDEAL problem solver (Bransford & Stein, 1984) describes problem solving as a uniform process of *i*dentifying potential problems, *d*efining and representing the problem, *e*xploring possible strategies, *a*cting on those strategies, and *l*ooking back and evaluating the effects of those activities.

Gick (1986) synthesized these and other problem-solving models (Greeno, 1980) into a simplified model of the problem-solving process, including the processes of constructing a problem representation, searching for solutions, and implementing and monitoring solutions. Although descriptively useful, these problem-solving models assume that all problems are solved in pretty much the same way and that these generalizable processes can be applied in different contexts with different types of problems in order to yield similar results. A serious weakness of general problem-solving approaches is their underestimation of the role of domain knowledge and thus pattern recognition (analogical reasoning) which has resulted in the misrepresentation of knowledge, thereby inhibiting far transfer, which is the true purpose of education and training. Treating problem solving as a reproducible, algorithmic process has failed to focus on the highest-value learning outcomes, which is certainly part of the reason that school learning and corporate training are often perceived as irrelevant and boring.

Among the most commonly referenced models of problem solving is that proposed by Polya (1957). In *How to Solve It*, Polya (1957) addressed some of the limitations of information-processing models of problem solving in his general problem-solving approach, even before they were conceived. He recommended four steps to solving mathematical problems:

1. understand the problem (what is being asked for; is there enough information);
2. make a plan (look for patterns; organize information);
3. carry out the plan;
4. evaluate its effectiveness.

Polya recommended numerous heuristics to improve problem solving, such as analogies (Can you find a similar problem?), induction (generalizing from examples of problems), and pattern matching (Have you solved a similar problem?). Many of his recommendations are described throughout this book. Analogies are described in Chapters 11 and 16. Induction is described in Chapter 9, and pattern recognition is described in Chapter 12.

For me, problem solving as a process also has two critical attributes. First, problem solving requires the mental representation of the problem, known as the problem space, problem schema (Chapter 15), or mental model of the problem. The problem space consists of a set of symbolic structures (the states of space) and the set of operators over the space (Newell, 1980; Newell & Simon, 1972). Once again, those states of space are easily identifiable in well-structured problems (see discussion below); however, they are much more difficult to identify for ill-structured problems. Problem spaces may be externalized as formal models (see Chapter 19 of this volume for descriptions of methods used to externalize problem representations). However represented, the construction of a mental model of the problem is one of the most critical problem-solving processes. In this book, I emphasize the importance of constructing mental models of the problem in order to understand the elements of the problems and how they interact as well as the procedures for solving a problem. Until the problem solver constructs a model of the problem in its context, a viable solution is only probable, while understanding and transfer are improbable. Second, problem solving requires some manipulation and testing of the mental model of the problem in order to generate a solution. Problem solvers act on the problem space in order to generate and test hypotheses and solutions.

Schema-theoretic conceptions of problem solving opened the door for different problem types by arguing that problem-solving skill is dependent on a schema for solving particular types of problems. The construction of those problem schemas results from the extraction and application of domain knowledge. If the learner possesses a complete schema for any problem type, then constructing the problem representation is simply a matter of mapping an existing problem schema onto a problem. Existing problem schemas are the result of previous experiences in solving particular types of problems, enabling the learner to proceed directly to the implementation stage of problem solving (Gick, 1986) and try out the activated solution. Experts are better problem solvers because they recognize different problem states that invoke certain solutions (Sweller, 1988). If the type of problem is recognized, then little searching through the problem space is required. Novices, who do not possess well-developed problem schemas, are not able to recognize problem types, so they must rely on weaker problem-solving strategies, such as means–ends analysis.

My theory of problem solving diverges from traditional approaches to problem solving that articulate single approaches to solving all kinds of problems. In the remainder of this chapter, I argue that problems and therefore problem-solving processes vary. The ways that physicians diagnose medical maladies is different from the ways that mechanical engineers design a new part for an automobile or the ways that we make personal decisions about our needs. Next, I describe how problems and problem solving vary.

HOW DO PROBLEMS VARY?

Problems and the methods and strategies used by individuals and groups to solve them, both in the everyday and classroom worlds, vary dramatically. Smith (1991) categorized factors that influence problem solving as external and internal. External factors are those related to the nature of the problem as encountered in the world. Internal factors are related to the personal characteristics of the problem solver, such as prior experience, prior knowledge, or strategies used. Problem solving varies both externally (the problem as it exists in the world) and internally (how the individual conceptualizes and resolves the problem). I will first describe external problem factors and later explicate some internal factors that are important to problem solving.

What External Factors Mediate Problem Solving?

Problems, as they are encountered in the world, differ in several important ways. Bassok (2003) described two important external attributes of problems: abstraction and continuity. Abstraction refers to the representation of the content and context of a problem that either facilitates or impedes analogical transfer of one problem to another. Most classroom problems are more abstract than most everyday problems, which are embedded in various contexts. Continuity of the problem is the degree to which attributes of problems remain the same or change over time (described later as dynamicity). High-continuity problems are more easily solved and transferred.

The primary reason for distinguishing among different kinds of problems is the assumption that solving different kinds of problems calls on distinctly different sets of skills (Greeno, 1980). Solving different kinds of problems entails different levels of certainty and risk (Wood, 1983). Given that different kinds of problems require different sets of skills, then learning to solve different kinds of problems will require different forms of instruction. In order to better understand how problems differ, I describe five external characteristics of problems:

1. structuredness;
2. context;
3. complexity;
4. dynamicity;
5. domain specificity.

What Is Structuredness of Problems?

Foremost among the differences among problems is the continuum of structuredness, between well-structured and ill-structured problems (Arlin, 1989; Jonassen, 1997, 2000c; Newell & Simon, 1972; Voss & Post, 1988). Most problems encountered in formal education are well-structured problems, while problems that occur in our everyday and professional lives tend to be more ill structured. It is important to note that structuredness represents a continuum, not a dichotomous variable. While well-structured problems tend to be associated with formal education and ill-structured problems tend to occur in the everyday world, that is not necessarily the case.

The most commonly encountered problems in formal educational contexts are well-structured problems. Typically found at the end of textbook chapters and on examinations, well-structured problems present all of the information needed to solve the problems in the problem representation; they require the application of a limited number of regular and circumscribed rules and principles that are organized in a predictive and prescriptive way; possess correct, convergent answers; and have a preferred, prescribed solution process (Wood, 1983). These problems have also been referred to as transformation problems (Greeno, 1980) that consist of a well-defined initial state, a known goal state, and a constrained set of logical operators.

Ill-structured problems, on the other hand, are the kinds of problems that are encountered in everyday life and work, so they are typically emergent and not self-contained. Because they are not constrained by the content domains being studied in classrooms, their solutions are not predictable or convergent. Ill-structured problems usually require the integration of several content domains; that is, they are usually interdisciplinary in nature. Workplace engineering problems, for example, are ill structured because they possess conflicting goals, multiple solution methods, non-engineering success standards, non-engineering constraints, unanticipated problems, distributed knowledge, collaborative activity systems, and multiple forms of problem representation (Jonassen, Strobel, & Lee, 2006). Ill-structured problems appear ill defined because one or more of the problem elements are unknown or not known with any degree of confidence (Wood, 1983); they possess multiple solutions, solution paths, or no solutions at all (Kitchner, 1983); they possess multiple criteria for evaluating solutions, so there is uncertainty about which concepts, rules, and principles are necessary for the solution and how they are organized; and they often require learners to make judgments and to express personal opinions or beliefs about the problem. Everyday, ill-structured problems are uniquely human interpersonal activities (Meacham & Emont, 1989) because they tend to be relevant to the personal interest of the problem solver who is solving the problem as a means to further ends (Chapman, 1994).

Although information-processing theories averred that “in general, the processes used to solve ill-structured problems are the same as those used to solve well structured problems” (Simon, 1978, p. 287), more recent research in situated and everyday problem solving makes clear distinctions between thinking required to solve well-structured problems and ill-structured problems. Allaire and Marsiske (2002) found that measures that predict well-structured problem solving could not predict the quality of solutions to ill-structured, everyday problems among elderly people. “Unlike formal problem solving, practical problem solving cannot be understood solely in terms of problem structure and mental representations” (Scribner, 1986, p. 28), but rather include aspects outside the problem space, such as environmental information or goals of the problem solver. Hong, Jonassen, and McGee (2003) found that solving ill-structured problems in an astronomy simulation called on different skills than well-structured problems, including metacognition (see Chapter 21) and argumentation (see Chapter 20). Argumentation is a social and communicative activity that is an essential form of reasoning in solving ill-structured, everyday problems (Chapman, 1994; see Chapter 21). Jonassen and Kwon (2001) showed that communication patterns in teams differed when solving well-structured and ill-structured problems. Finally, groups of students solving ill-structured economics problems produced more extensive arguments than when solving well-structured problems because of the importance of generating and supporting alternative solutions when solving ill-structured problems (Cho & Jonassen, 2002). Clearly more research is needed to substantiate these differences, yet it appears that well-structured and ill-structured problem solving engage substantively different cognitive processes.

The structuredness of problems is significantly related to the situatedness of problems. That is, well-structured problems tend to be more abstract and decontextualized and not situated in any meaningful context, relying more on defined rules and less on context. On the other hand, ill-structured problems tend to be more embedded in and defined by everyday or workplace situations, making them more subject to belief systems that are engendered by social, cultural, and organizational drivers in the context (Jonassen, 2000c; Meacham & Emont, 1989; Smith, 1991). The role of problem context is described next.

What Is Context of Problems?

In everyday problems that tend to be more ill structured, context plays a much more significant role in the cognitive activities engaged by the problem (Lave, 1988; Rogoff & Lave, 1984). The context in which problems are embedded becomes a significant part of the problem and necessarily part of its solution (Wood, 1983). Well-structured problems, such as story problems (described later), embed problems in shallow story contexts that have little meaning or relevance to learners. Workplace engineering problems are made more ill structured because the context often creates unanticipated problems (Jonassen et al., 2006). Very ill-structured problems, such as design problems, are so context-dependent that the problems have no meaning outside the context in which they occur.

The role of context defines the situatedness of problems. Situatedness is concerned with the situation described in the problem (Hegarty, Mayer, & Monk, 1995). Rohlfing, Rehm, and Goecke (2003) defined situatedness as a specific situation in which problem-solving activity occurs, contrasting it with the larger, more stable context that supplies certain patterns of behavior and analysis for situations to be confronted with. Any situation may be constrained by several, overlapping contexts. That is why everyday problems are often more difficult to solve, yet they are more meaningful. Situativity theorists claim that when ideas are extracted from an authentic context, they lose meaning. The problem solver must accommodate multiple belief systems embedded in different contexts.

What Is Complexity of Problems?

Problems also vary in complexity. According to Meacham and Emont (1989), problems vary in terms of complexity. Complexity is an interaction between internal and external factors. Problem-solving complexity is a function of how the problem solver interacts with the problem, determined partially by the problem solver's experience as they interact with the problem, importance (degree to which the problem is significant and meaningful to a problem solver), and urgency (how soon the problem should be solved). The choices that problem solvers make regarding these factors determines how difficult everyday problems are to solve. Ill-structured problems tend to be more difficult to solve, in part because they tend to be more complex. The more complex that problems are, the more difficulty students have to choose the best solution method (Jacobs, Dolmans, Wolfhagen, & Scherpbier, 2003). Also, problem solvers represent complex problems in different ways that lead to different kinds of solutions (Voss, Wolfe, Lawrence, & Engle, 1991).

At the base level, problem complexity is a function of external factors, such as the number of issues, functions, or variables involved in the problem; the number of interactions among those issues, functions, or variables; and the predictability of the behavior of those issues, functions, or variables. Although complexity and structuredness invariably overlap, complexity is more concerned with how many components are represented implicitly or explicitly in the problem, how those components interact, and how consistently they behave. Complexity has direct implications for working memory requirements as well as comprehension. Complex problems impose more cognitive load on the problem solver. The more complex a problem, the more difficult it will be for the problem solver to actively process the components of the problem. Most well-structured problems, such as textbook math and science problems, are not very complex. They involve a constrained set of factors or variables. While ill-structured problems tend to be more complex, well-structured problems can be extremely complex and ill-structured problems fairly simple. For example, chess is a very complex, well-structured problem, and selecting what to wear from our closets (at least for me) is a simple, ill-structured problem. Complexity is clearly related to structuredness, though it is a sufficiently independent factor to warrant consideration because of the working memory requirements.

Complexity can also be described in terms of the processing required to solve the problem. For example, Wood (1985) suggested that there are three kinds of problem complexity: (1) component complexity, (2) coordinative complexity, and (3) dynamic complexity. Component complexity describes the number of distinct acts required to solve the problems along with the diversity of kinds of information needed to perform these acts. Coordinative complexity described the variety of relationships among problem-solving acts. Dynamic complexity describes changes in those relationships over time. I see dynamicity as a separate external factor, described next.

In a more recent analysis, Jonassen and Hung (2008) described problem complexity in terms of internal and external factors. Internal factors included the breadth of knowledge required to solve the problem, the attainment level of the problem solver, and the level of domain knowledge. External factors included:

- the intricacy of problem–solution procedures;
- the relational complexity among domain concepts;
- the level of intransparency (unknowns in the problem space);
- the heterogeneity of problem interpretations;
- the interdisciplinarity, dynamicity, and legitimacy of alternative solutions.

Ill-structured problems tend to be more complex; however, there exist a number of highly complex well-structured problems.

What Is Dynamicity of Problems?

Dynamicity may be thought of as another dimension of problem complexity. In dynamic problems, the relationships among variables or factors change over time. Changes in one factor may cause variable changes in other factors that often substantively changes the nature of the problem. In engineering problems, for example, unanticipated problems and changing solution criteria plague problem solvers (Jonassen et al., 2006). With everyday or workplace problems, it is often difficult to determine what the problem is because problems change in light of new developments (Roth & McGinn, 1997). That is, many problems are dynamic because their conditions or contexts change over time, converting them into different problems. The more intricate these interactions, the more difficult it is to develop or implement any solution. Ill-structured problems tend to be more dynamic than well-structured problems that tend to be static.

What Are Domain and Context Specificity of Problems?

A final dimension of problems and problem solving is domain and context specificity. In contemporary psychology, there is a common belief that problems within a domain rely on cognitive strategies that are specific to that domain (Mayer, 1992; Smith, 1991; Sternberg & Frensch, 1991). These are often referred to as strong methods, as opposed to domain-general strategies (weak methods). For example, Lehman, Lempert, and Nisbett (1988) concluded that different forms of reasoning are learned in different graduate disciplines. Graduate students in the probabilistic sciences of psychology and medicine perform better on statistical, methodological, and conditional reasoning problems than students in law and chemistry, who do not learn such forms of reasoning. The cognitive operations are learned through the development of pragmatic reasoning schemas rather than exercises in formal logic. Graduates in different domains develop reasoning skills through solving situated, ill-structured problems that require forms of logic that are domain-specific.

Problem solving also varies by context. Elstein, Shulman, and Sprafka (1978) found that medical diagnosis is specific to a particular context. Thus, a doctor who works in Boston may not be very successful in Mogadishu. Context affects the nature of social interactions as well as cognitive processing. Learning the illness scripts in new contexts impacts the learning experience.

WHAT KINDS OF PROBLEMS ARE THERE?

Perhaps most characteristic of my work on problem solving that distinguishes it from previous research efforts is the underlying assumption that there are different kinds of problems. Jonassen (2000c) identified eleven kinds of problems:

1. logic problems;
2. algorithms;
3. story problems;
4. rule-using/rule-induction problems;
5. decision making;
6. troubleshooting;
7. diagnosis-solution problems;
8. strategic performance;
9. policy-analysis problems;
10. design problems;
11. dilemmas.

That typology represents a developmental theory of problem solving. How discrete each kind of problem is, or whether additional kinds of problems exist is not certain. As illustrated in Figure 1.1, the problems

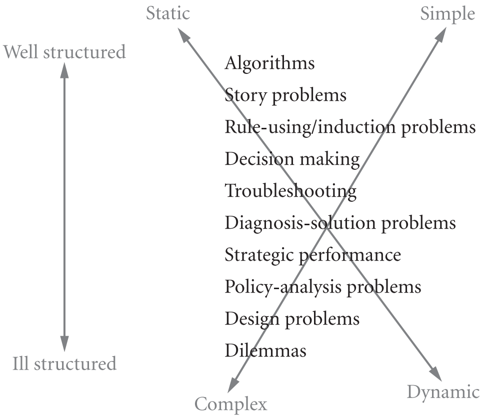


Figure 1.1 Typology of problems.

in this typology vary primarily along a continuum from well structured to ill structured. Well-structured problems tend to be more static and simple, while ill-structured problems tend to be more complex and dynamic. Although structuredness, complexity, and dynamicity are related, there exist many problems which are less related. In the following sections, I briefly describe some of these kinds of problems.

What Are Logic Problems?

Logic problems tend to be abstract tests of logic that puzzle the learner. They are used to assess mental acuity, clarity, and logical reasoning. Classic games such as missionaries and cannibals or tower of Hanoi challenge learners to find the most efficient (least number of moves) sequence of action. Rubik's Cube was a popular game in the 1970s requiring the user to rotate the rows and columns of a three-dimensional cube to form patterns. In each of these "problems," there is a specific method of reasoning that will yield the most efficient solution. It is up to the learner to discover that method. Research has shown that the ability to solve these problems does not transfer to other kinds of problems (Hayes & Simon, 1977; Reed, Ernst, & Banerji, 1974).

Logic problems can be decidedly more complex than these. Popular card games such as bridge or hearts and board games such as checkers and chess are more complex forms of logic problems. These games employ more complex rules and constraints. Many computer games also represent complex logic problems, albeit embedded in realistic or fantasy contexts. These more complex forms of problems also require other forms of problem solving, including rule using, diagnosis-solution, and perhaps design. However, few if any logical problems are embedded in any common situation, making them necessarily more abstract and therefore less transferable. Logic problems have been the focus of considerable psychological research. However, the usefulness of that research to instructional design is limited by their lack of relevance to education or training.

What Are Algorithms?

One of the most common problem types encountered in schools is the algorithm. Most common in mathematics courses, students are taught to solve problems using a finite and rigid set of procedures with limited, predictive decisions. Solving algorithms requires number comprehension, number production, and calculation (McCloskey, Caramaza, & Basili, 1985). These are the skills required to complete calculations. Calculations, according to McCloskey et al. (1985), require comprehension of the operations (e.g., associative and commutative properties and concepts of multiplication and division), execution procedures for calculating, and retrieval of arithmetic facts (e.g., times tables). Such algorithmic approaches are also commonly used in science courses or in home economics. For example, most recipes are algorithms for cooking. It is likely that a model similar to that proposed by McCloskey et al. can be generated for non-mathematical forms of algorithmic problems.

As argued in Chapter 2 on story problems, over-reliance on algorithmic problem representations often results in the absence of conceptual understanding of the objects the algorithm is representing. Content that is learned only as an algorithmic procedure can rarely be transferred because of a lack of conceptual understanding of the underlying processes. Stated more assertively, purely algorithmic teaching does damage, because it inhibits later learning and self-sufficient learning or adaptation. This is a common complaint about learning statistics, where professors focus on the algorithms and miss the purpose of studying the statistical analysis. It is pandemic in mathematics courses, where students learn to perform complex process, such as derivations and integrations without understanding the purpose of either. Learners who are adept at abstract reasoning can develop some conceptual understanding of increasingly complex algorithms, such as those encountered in calculus, trigonometry, and other mathematics domains. Most of us are limited in our ability to create such abstract representations of procedures, so we never develop meaning for mathematics.

Many researchers, such as Smith (1991), argue that algorithms (repeating a series of steps) are, by nature, not problems but rather procedures. When learners are required to select and perhaps modify an algorithm for use in an exercise, it may become problem solving. Therefore, for purposes of this book, algorithms will not be considered further.

What Are Story Problems?

In an attempt to make problem solving more meaningful, textbook authors, teachers, and professors assign story problems to students. These can be found at the backs of textbook chapters in virtually every science, mathematics, and engineering textbook in existence. Traditional methods for solving story problems require learners to (1) represent the unknowns by letters; (2) translate relationships about unknowns into equations; (3) solve the equations to find the value of the unknowns; and (4) verify values found to see if they fit the original problem (Rich, 1960). Unfortunately, it is the unsuccessful problem solvers who base their solution plans on the numbers and keywords that they select from the problem (Hegarty et al., 1995). This linear process implies that solving problems is a procedure to be memorized, practiced, and habituated and that emphasizes answer getting, not meaning making (Wilson, Fernandez, & Hadaway, 2001). Transferring that process to new contexts is very difficult for learners because they focus too closely on surface features or recall familiar solutions from previously solved problems (Woods, Hrymak, Marshall, Wood, Crowe, Hoffman, et al., 1997). They fail to understand the principles and the conceptual applications underlying the performance, so they are unable to transfer the ability to solve one kind of problem to problems with the same structure but dissimilar features. Jonassen (2003) has articulated a model for designing technology-enhanced story problem-solving environments, including a set identifier, situational model, structural model builder, equation builder, and different representations of problem outcomes. The environment integrates qualitative and quantitative problem representations and requires that learners construct a conceptual model of the problem that integrates the situational (story) content with an understanding of the semantic structure of the problem based on the science principles. Story problems are further described in Chapter 2.

What Are Rule-Using/Rule-Induction Problems?

Many problems have correct solutions but multiple solution paths or multiple rules governing the process. They tend to have a clear purpose or goal that is constrained but not restricted to a specific procedure or method. Using an online search system or a library catalog to find scientific information are examples of rule-using problems. The purpose is clear: find the most relevant information sources in the least amount of time. That requires selection of search terms, constructing effective search arguments, implementing the search strategy, and evaluating the utility and credibility of information found. Schacter, Chung, and Dorr (1998) found that students rarely employ systematic search strategies and spend little to no time planning their searches. Strategy is the essence of rule-oriented problems. Given that there are multiple search strategies that are possible, rule-using problems can become decidedly more ill structured.

Many problems require that learners induce rules in order to solve problems. When encountering a new machine or system, it is necessary to figure out how the system works, that is, to induce the rules that describe how the system functions. Learning how to use transportation systems in foreign countries poses myriad rule-induction problems. Qualitative-analysis labs in chemistry provide students unknown compounds on which they conduct numerous tests in order to discover the identity of the compound. Those tests represent rules that are defined by the causal relationships among the chemical elements (see Chapter 17 for a description of causal reasoning). Doing so requires that they induce rules that describe the behavior of various reagents. These are generally perceived as more difficult problems than applying rules, although the level of experienced difficulty depends on individual differences in cognition.

What Are Decision-Making Problems?

Decision-making problems usually require that problem solvers select a solution from a set of alternative solutions. Traditional conceptions of decision making posit a set of alternative criteria that decision makers work through in order to identify the optimal solution. Those criteria may be provided to the problem solver(s), or the solver(s) may have to identify the most relevant criteria. Everyday life is replete with decision-making problems. Which health policy should I choose? Which school should my daughter attend in order to maximize her chances for acceptance into a good college? Businesses also daily solve many decision-making problems, such as selecting a new part vendor or other contractor, determining inventory levels, selecting appropriate testing methods, or awarding prizes for research. Though these problems typically require selecting one solution, the number of decision factors to be considered in deciding among those solutions as well as the weights assigned to them can be very complex. As we will see in Chapter 3, those rational-choice models of decision making are not always descriptive of how most of us actually make decisions.

What Are Troubleshooting Problems?

Troubleshooting is one of the most common forms of everyday problem solving. Although troubleshooting is most commonly associated with technician-level jobs (maintaining complex communications and avionics equipment, repairing computer equipment), professionals also engage in troubleshooting faulty systems (e.g., engineers identifying faults in chemical processes; physicians or psychotherapists diagnosing medical or psychological problems; communication specialists troubleshooting a dysfunctional committee).

Although troubleshooting is most commonly taught as a procedure, it requires a combination of domain and system knowledge (conceptual models of the system including system components and interactions), flow control, fault states (fault characteristics, symptoms, contextual information, and probabilities of occurrence); troubleshooting strategies such as search and replace, serial elimination, and space splitting; and fault testing procedures. These skills are integrated and organized by the troubleshooter's experiences. As troubleshooters gain experience, their knowledge becomes indexed by those experiences rather than by any conceptual models of domain knowledge. Jonassen and Hung (2006) have articulated a research-based model for designing troubleshooting learning environments that includes a multi-layered conceptual model of the system, a simulator for hypothesis generation and testing, and a case library of stories from other troubleshooters. Troubleshooting problems are further described in Chapter 4.

What Are Diagnosis-Solution Problems?

The first part of diagnosis-solution problems, diagnosis, is quite similar to troubleshooting. Most diagnosis-solution problems require identifying a fault state, just like troubleshooting. However, in troubleshooting, the goal is to repair the fault and to get the system back online as soon as possible, so the solution strategies are more restrictive. Diagnosis-solution problems usually begin with a fault state similar to troubleshooting (e.g., symptoms of a sick person). The physician examines the patient and considers patient history before making an initial diagnosis. In a spiral of data collection, hypothesis generation and testing, the physician focuses in a specific etiology and differential diagnosis of the patient's problem. At that point, the physician must suggest a solution. Frequently, there are multiple solutions and solution options that are imposed by the patient, the institution in which the physician is working, the insurance company, and many others. It is this ambiguity in solution options that distinguishes diagnosis-solution problems from troubleshooting. Note that as physicians gain experience, the diagnostic process becomes more of a process of pattern recognition.

What Are Strategic Performance Problems?

Strategic performance entails real-time, complex activity structures where the performers apply a number of tactical activities to meet a more complex and ill-structured strategy, usually under significant time pressure. In order to achieve the strategic objective, such as flying a combat airplane or quarterbacking a professional football offense, the performer applies a set of complex tactical activities designed to meet strategic objectives. Strategy formation represents a situated case or design problem (described next). Meeting that strategy through tactical maneuvers is a tactical performance. Typically there are a finite number of tactical activities that have been designed to accomplish the strategy; however, the mark of an expert tactical performer is his or her ability to improvise or construct new tactics on the spot to meet the strategy. The quarterback who calls an audible at the line of scrimmage is selecting a new tactic to meet the offensive strategy. In battlefield situations, superior officers identify a strategy and may negotiate tactical concerns with the performer; however, both realize that tactics may have to be adjusted. Those adjustments are contextually constrained. Strategic performances can be quite complex yet performed in real time. The options can be quite numerous and their implementation quite complex. Strategic performance problems will be further described in Chapter 5.

What Are Policy Problems?

Most public problems that are described on the pages of newspapers or in news magazines are complex, multi-faceted issues on which multiple positions and perspectives exist. Foreign-policy issues at the national level, legal issues at the state levels, and economic and development issues at the local level are examples of policy problems. Classical situated policy problems also exist in international relations, such as, "Given low crop productivity in the Soviet Union, how would the solver go about improving crop productivity if he or she served as Director of the Ministry of Agriculture in the Soviet Union?" (Voss and Post, 1988, p. 273).

What makes these problems difficult to solve is that it is not always clear what the problem is or that different entities and agencies conceive of the problem differently. Because defining the problem space is more ambiguous, policy problems are more ill structured. Policy problems require the solver to articulate the nature of the problem and the different perspectives that impact the problem before suggesting solutions (Jonassen, 1997). They are more contextually bound than any kind of problem considered so far and so are ill structured. That is, their solutions rely on an analysis of contextual factors. Justifying policy decisions is among the most important processes in solving case problems. Policy problems will be further described in Chapter 6.

What Are Design Problems?

Perhaps the most ill-structured kind of problem is design (Jonassen, 2000c). Whether it be an electronic circuit, a mechanical part, a new manufacturing system, or a symphony, design requires applying a great deal of domain knowledge with a lot of strategic knowledge, resulting in an original design. Despite the apparent goal of finding an optimal solution within determined constraints, design problems usually have vaguely defined or unclear goals with unstated constraints. They possess multiple solutions, with multiple solution paths. Perhaps the most vexing part of design problems is that they possess multiple criteria for evaluating solutions, and these criteria are often unknown. Ultimately, the designer must please the client; however, the criteria for an acceptable design are usually unstated. Design problems often require the designer to make judgments about the problem and to defend them or to express personal opinions or beliefs about the problem, so ill-structured problems are uniquely human interpersonal activities (Meacham & Emont, 1989).

Generic design processes include articulating the problem space, specifying functional requirements, applying prior knowledge, analyzing constraints, selecting a solution, constructing a model or artifact, and optimizing the solution. Because design is so domain or context specific, these processes assume many different forms. Design literature comes from product design, architectural design, engineering design, and instructional design. Each literature base begins with different assumptions and prescribes different processes and methods. Designing a bridge and designing a chemical process are so different that they share little knowledge and skills in common. Design problems will be further described in Chapter 7.

What Are Dilemmas?

All of us in different contexts are subject to social or ethical dilemmas. Creating a biochemical product that is profitable but environmentally injurious represents a dilemma. Society has wrestled with ethical dilemmas, such as abortion and same-sex marriage, for years. Dilemmas may be the most ill structured and unpredictable, often because there is no solution that will ever be acceptable to a significant portion of the people affected by the problem. Usually there are many valuable perspectives on the situation (economic, political, social, religious, ethical, etc.); however, none compels an acceptable solution to the problem. The situation is so complex and unpredictable that no best solution can ever be known. That does not mean that there are not many solutions, which can be attempted with variable degrees of success; however, none will ever meet the needs of the majority of people or escape the prospects of catastrophe. Dilemmas are often complex, social situations with conflicting perspectives, and they are usually the most vexing of problems.

How Do Discrete Problems Aggregate?

The problem types just described are conveyed as discrete problems that occur in isolation to each other. While discrete problems are most commonly solved in formal educational institutions, everyday and professional problems typically are aggregates of problems to be solved. Problems in the workplace are rarely discrete and individual. Rather, problems aggregate so the parameters of the problems are not easily isolated. Jonassen et al. (2006) found that most engineering problems consisted of numerous better-structured problems, each of which had to be solved in some sequence. Problem aggregates are problem clusters related to the same work activities. For example, developing a computer system requires solving a host of design, troubleshooting, and case problems. Starting a business likewise represents myriad decision-making and design problems. Problems in everyday and professional contexts are generally problem aggregates, so when analyzing any problem context it is necessary to identify both the problem aggregates and the problems that constitute the problem aggregate.

Note that in Part I of this book, where I describe problem types in depth, I have focused on a limited set of problem types. For some of the problem types described above, there is a lack of empirical and theoretical research to support recommendations, so I explicate the better known kinds of problems.

HOW DO PROBLEM SOLVERS VARY?

As stated before, Smith (1991) identified both external and internal factors in problem solving. The internal factors relate to the cognitive and affective dispositions of the problem solvers. Solving problems, simple or complex, engages a variety of cognitive skills, which are necessarily mediated by numerous individual differences. Those differences include different forms of intelligence, cognitive capacities, and personality characteristics (Jonassen & Grabowski, 1993). Numerous researchers have attempted to isolate the most important differences. For example, Arlin (1989) claimed that intensity, temporality, and familiarity were the most predictive attributes of problem-solving abilities. Intensity refers to the level of motivation and effort that a problem solver invests in the problem based on the appeal or interest of the problem to the problem solvers. Temporality refers to the ability of the problem solver to remember similar problems encountered in the past, thereby requiring fewer cognitive resources to solve. Familiarity is the level of experiences that the problem solver has had with similar problems. Very familiar problems require relatively automated processing. Treating problems similarly enables the problem solver to distinguish various types of problems and more efficiently to use previously applied solutions. Although hundreds of individual differences that may affect problem-solving ability have been identified and researched, the three primary individual differences that mediate the ability of learners or practitioners to solve ill-structured problems (I believe) are:

1. prior domain knowledge;
2. prior experience in solving similar problems;
3. cognitive skills (especially causal reasoning, analogical reasoning, and epistemological beliefs).

Note that motivation and affect play a significant role in problem solving. Learners' motivation affects their willingness to engage and persist on problem-solving tasks. As indicated in the Introduction, these variables represent another dimension of problem solving that is beyond the scope of this book and my expertise.

What Is the Effect of Domain Knowledge on Problem Solving?

Cognitive researchers agree that the learner's prior domain knowledge is among the most important determinants of problem-solving ability (Greeno, 1980; Hayes, 1989; Rittle-Johnson & Alibali, 1999). However, all of that research was conducted using well-structured problems. With all problems, it is not just quantity of knowledge possessed by problem solvers but also the quality that matters. In order to solve any problem, problem solvers must possess better-integrated conceptual frameworks for domain knowledge that accommodate multiple perspectives, methods, and solutions. Here problem-solving research should be well informed by conceptual change research. Learners synthesize more complex and integrated conceptual models of the world from naive understandings that have been challenged by conflicting information (Vosniadou, 1992). Well-developed conceptual models necessitate conceptually oriented instruction and experiences used to prepare problem solvers.

It is also important to note that domain knowledge is almost never sufficient to solve problems (Roth & McGinn, 1997). Problem-solving skills also rely on experience, reasoning skills, and epistemological development.

What Is the Effect of Prior Experience on Problem Solving?

Experience is the most common metric for identifying expertise (Smith, 1991). As indicated in Chapter 12, recalling experiences of solving specific kinds of problems is the most frequent strategy for failure diagnosis (Konradt, 1995). Experts' first search for and then reuse prior experiences when solving problems, where symptoms observed in previous situations are collected and compared with those in similar and current situations. Bereiter and Miller (1989) found that problem solvers base their problem identification on their beliefs about the cause once a discrepant symptom is found. Those beliefs are based on historical experience. They also found that the most common reason for taking a particular action during troubleshooting is to test for the most common problem based on experience. Physicians, for example, shorten their diagnostic process by applying their historical knowledge (known as illness scripts) of specific fault tendencies in recognizing patterns of symptoms. The role of prior experience in problem solving is more completely described in Chapter 12.

Experiences are phenomenological and are normally conveyed through stories. For example, when troubleshooting complex systems, technicians tell stories because "the hardest part of diagnosis is making sense out of a fundamentally ambiguous set of facts, and this is done through a narrative process to produce a coherent account" (Orr, 1996, p. 186). Therefore, Jonassen and Hung (2006) recommend the use of case libraries of stories about how experienced problem solvers have solved similar problems. Case libraries, based on principles of case-based reasoning, represent one of the most powerful forms of instructional support for ill-structured problems such as troubleshooting (Jonassen & Hernandez-Serrano, 2002). Hernandez-Serrano and Jonassen (2003) found that students who accessed experts' stories of similar product-development problems outperformed control group learners on prediction, inference, explanation, and inference questions.

Case libraries provide viable substitutes for experience when learning to solve ill-structured problems.

Which Thinking/Reasoning Skills Affect Problems Solving?

The underlying assumption of my work is that different kinds of problem solving entail different kinds of cognition: different knowledge, different forms of knowledge representation, and different thinking skills. It is impossible to isolate and explicate all of the thinking processes entailed by every kind of problem in every context. However, the cognitive processes that enable learners to solve problems are the construction of problem schemas (Chapter 15), analogical reasoning (Chapter 16), causal reasoning (Chapter 17), and argumentation (Chapter 20).

The dominant theory of analogical reasoning applied to problem solving is structure-mapping theory (Gentner, 1983), where mapping the structure of the prior problem to the problem being solved independent of the surface objects is required for learning from experience. In order to do so, those surface features (which attract the attention of poor problem solvers) must be discarded. Then the higher-order, systemic relations must be compared on a one-to-one basis in the example and the problem. Learning by drawing structural comparisons across two examples (analogical encoding) has been shown to be the most effective method for reasoning by analogy (Gentner, Loewenstein, & Thompson, 2003).

The cognitive process that underlies all scientific thinking is causal reasoning (Carey, 2002; Keil, 1989), what Hume (1938, p. 9) called "the cement of the universe." Relationships among the conceptual entities in every scientific domain are primarily causal. In order to make predictions, draw inferences or implications, or explain phenomena in every scientific domain, learners must understand the cause–effect relationships among the phenomena in any problem in order to learn to transfer any skill in solving problems. Deep understanding of causal relationships requires the ability to convey multiple attributes of causality (Jonassen & Ionas, 2008).

Argumentation is essential for solving ill-structured problems. The arguments that students construct also provide the best evidence of learning and problem-solving in ill-structured problems.

In Part III of this book, I also describe important cognitive skills that facilitate problem solving, including questioning, modeling, and argumentation. These skills enable learners to construct robust problem schemas, analogically to compare problems, and to explicate the causal structure of problems.

What Is the Effect of Epistemological Development on Problem Solving?

Also known as intellectual maturity, epistemic beliefs, and intellectual development, epistemological development describes one's beliefs about the meaning of epistemological constructs, such as knowledge and truth and how those beliefs change over time (Hofer & Pintrich, 1997). There are several stage theories for describing learners' levels of epistemological development, including epistemological reflection (Baxter-Magolda, 1987), reflective judgment (King & Kitchener, 1994), and Perry's levels of intellectual development (Perry, 1970). While the theories differ in detail and scope, they suggest a common pattern of development that progresses from simple, black and white thinking, through an exploration of multiple perspectives, to complex, relativistic thinking.

Although epistemological development of learners and problem solvers probably does not mediate understanding of and performance on well-structured problems, most researchers believe that they play an important role in solving ill-structured problems (Wood, Kitchener, & Jensen, 2002). Dunkle, Schraw, and Bendixen (1995) found that performance in solving well-defined problems is independent of performance on ill-defined tasks, because ill-defined problems engaged a different set of epistemological beliefs than well-structured problems. Because ill-structured problems require accommodation of different perspectives and the use of argumentation (Chapman, 1994; Hong et al., 2003), generating solutions for ill-structured problems requires higher levels of epistemological development.

PART I

PROBLEM-SPECIFIC DESIGN MODELS

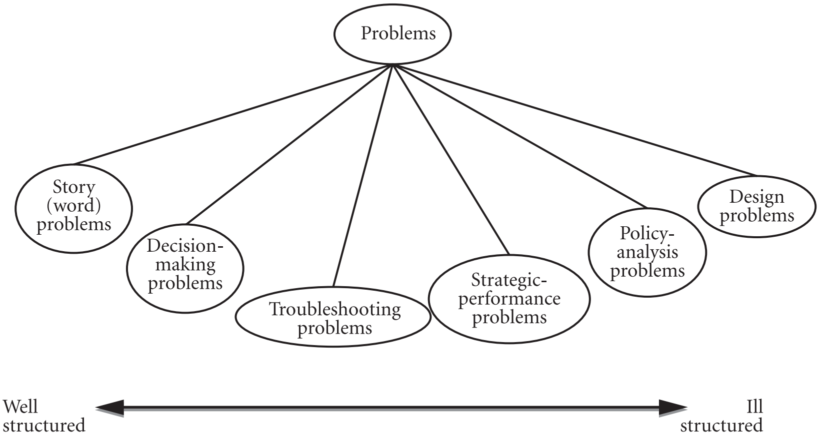


Figure I.1

As described in Chapter 1, I claim that there are different kinds of problems. In Part I of this book, I describe those different kinds of problems and recommend models for designing problem-solving learning environments. Those models call on the inclusion of different kinds of cases described in Part II and different cognitive strategies described in Part III.

2

STORY PROBLEMS

Story problems are the most common kind of problem encountered by students in formal education. Although not the most innovative or the most authentic, they are clearly the most commonly solved kind of problem in schools and universities as well as the most extensively researched. Students begin solving story problems in early elementary school and often encounter them through graduate school. From simple combined problems in beginning mathematics (e.g., Tom has three apples. Mary gave Tom three more apples. How many apples does Tom have in the end? [Riley, Greeno, & Heller, 1983]) to complex problems in thermodynamics, story problems are the most common kind of problem in formal education. Many innovations in mathematics and science education have attempted to replace story problems with more complex and authentic problems. Notwithstanding those innovations, story problems remain the most ubiquitous kind of problem solved in schools and universities.

HOW DO STUDENTS SOLVE STORY PROBLEMS?

Story problems typically present a set of variables embedded within a shallow story context. Story problems are normally solved by identifying key values in the short scenario, selecting the appropriate algorithm, applying the algorithm to generate a quantitative answer, and hopefully checking their responses (Sherrill, 1983). Despite our understanding of the requirements for solving and transferring story problems, learners usually employ a more tactical, problem-avoidance strategy to solving word problems:

1. Search for key words.
2. Select algorithm (formula) based on key words.
3. Apply the algorithm.

(Sherrill, 1983)

Rich (1960) elaborated that process slightly:

1. Represent the unknowns with letters.
2. Translate relationships about unknowns into equations.
3. Solve equations to find the value of the unknowns.
4. Verify or check the values calculated to see if they fit the original problem.

The solutions to story problems emphasize the quantitative representation of the problem, that is, the conversion of the values in the story into a formula, because that is what they are expected to do. The students are smart enough to realize what is rewarded, so this is what they do.

Based on that approach, it was formerly believed that children's major difficulty in solving word problems was their inability to select and apply the appropriate arithmetic operations (Zweng, 1979). Unfortunately, it is only the unsuccessful problem solvers who base their solution plans on the numbers and key words that they select from problem (Hegarty, Mayer, & Monk, 1995). When problem solvers attempt to directly translate the key propositions in the problem statement into a set of computations, known as the direct translation strategy, they more frequently commit errors. Why? This translation process is difficult. Converting semantic entities from a shallow story into a mathematical representation is difficult, but solving story problems requires more than the transformation of values into formulas. Rather, successful problem solving requires the comprehension of relevant textual information, the capacity to visualize the data, the capacity to recognize the deep structure of the problem, the capacity to correctly sequence their solution activities, and the capacity and willingness to evaluate the procedure used to solve the problem (Lucangeli, Tressoldi, & Cendron, 1998). Solving problems is more complex than plugging values into formulas and solving for the unknown. The complexity of the solution process suggested by Lucangeli et al. (1998) explains many of the difficulties that students have when they use a direct translation strategy to solve story problems.

Contemporary approaches to story problem solving have emphasized conceptual understanding of the story problems before attempting any solution. Successful problem solving requires the construction of a conceptual model of the problem and the application of solution plans that are based on those models. It is the quality of their conceptual models that most influences the ease and accuracy with which the problem can be solved (Hayes & Simon, 1976). Those conceptual models, also known as problem schemas (see Chapter 15 for a description of problem schemas), are mental representations of the pattern of information that is represented in the problem (Riley & Greeno, 1988). In order to solve story problems consistently, learners must demonstrate conceptual understanding of the problem types by constructing a conceptual model that includes a situational model of the problem, a structural model of the problem, and an algorithmic model (formula) of the problem from the problem text (Reusser, 1993). Because students normally make no effort to construct any kind of conceptual model of the problem, they commit errors and are unable to transfer any correct problem solutions to similar problems. Sherrill (1983) found that although students can identify key words in story problems, they frequently:

- select either the wrong algorithm or the wrong sequence of algorithms;
- select the proper algorithm, but use the wrong numbers;
- select the proper algorithm, apply the algorithm properly, and stop, not realizing that it was a multi-step problem;
- do not check their answers; and
- make little use of heuristics.

These responses all reflect an inadequate conceptual understanding of the problems or the problem-solving process. Such weaknesses in story problem solving can only be resolved by employing a more conceptually oriented approach to learning to solve story problems. That is the purpose of this chapter.

Next, I examine the role of conceptual models (problem schemas) in solving story problems.

HOW SHOULD STUDENTS SOLVE STORY PROBLEMS?

Figure 2.1 illustrates a conceptually oriented model for solving story problems. According to this approach, transferring story problem-solving skills depends on students constructing a conceptual model of the story problems they are required to solve and accessing that model when they are required to solve structurally congruent problems. When parsing the problem statement, students should search for

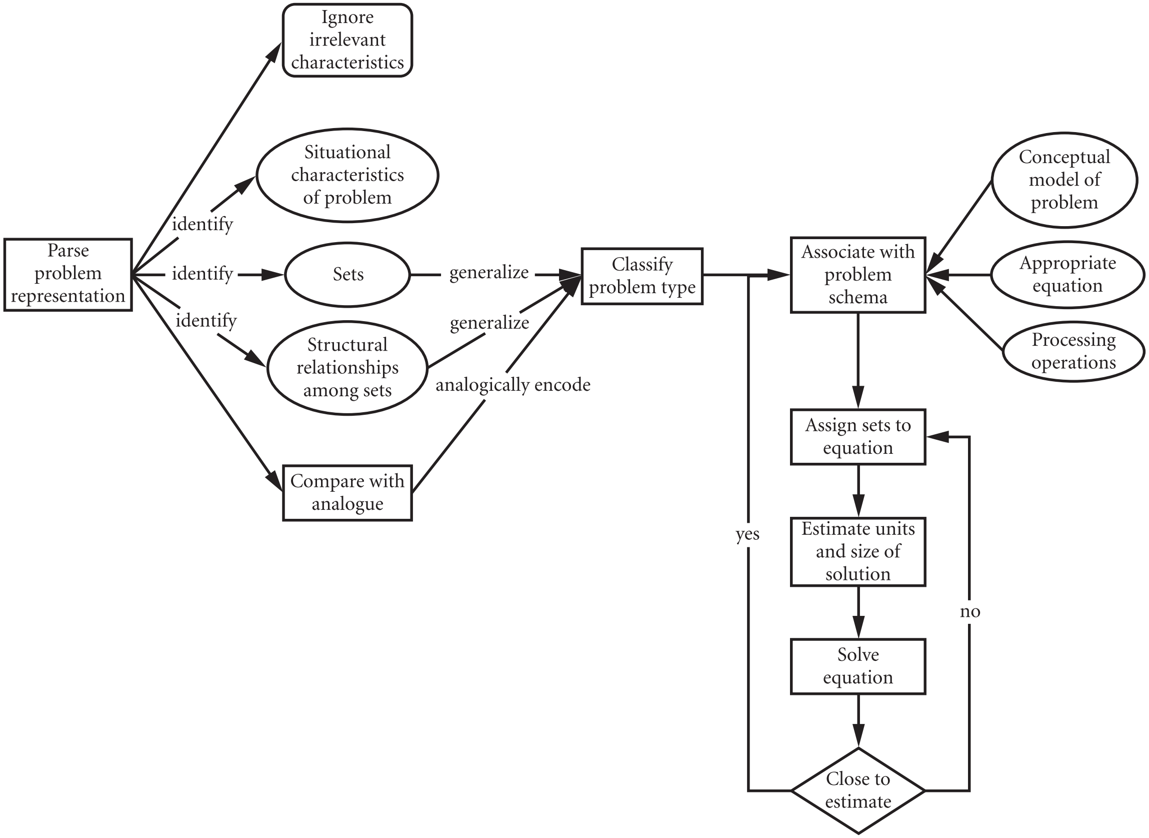


Figure 2.1 Story problem-solving process.

an appropriate conceptual model of the problem. To do that, students must identify the sets of values presented in the problem and determine their situational and structural characteristics and associate them with problem schemas. As illustrated in Figure 2.1, searching for a problem schema involves identifying the sets or elements contained in the problem, identifying the relationships among those elements, and identifying the situational characteristics. When an appropriate problem schema is accessed, the student can then successfully classify the type of problem. It is important that students ignore the irrelevant situational characteristics and classify the problem type based on the relevant structural properties. Correctly classifying the problem type is facilitated by analogically comparing pairs of problems (see Chapters 11 and 16 for a description of cases as analogues and analogical encoding processes). With a problem schema in mind, students can then access their conceptual model of that problem type, which is the key to solving story problems. From that conceptual model of the problem, students can retrieve the processing operations necessary to solve the problem, including any strategic knowledge about when to apply problem schemas and formulas. After assigning the sets to a model of the structural relationships between the sets in the problem, those sets are transferred to a formula directly associated with the structural model of the problem. Students then estimate the size of the result, solve the formula, and reconcile it to the estimate. If the solution was successful, students should work on developing strong associations between the new problem and the problem schema to better elaborate their conceptual model of that problem type.

HOW CAN STORY PROBLEM SOLVING BE SUPPORTED?

Given the description of the story problem-solving process in Figure 2.1, I next describe the essential components of a story-problem learning environment and present relevant research findings to support those components.

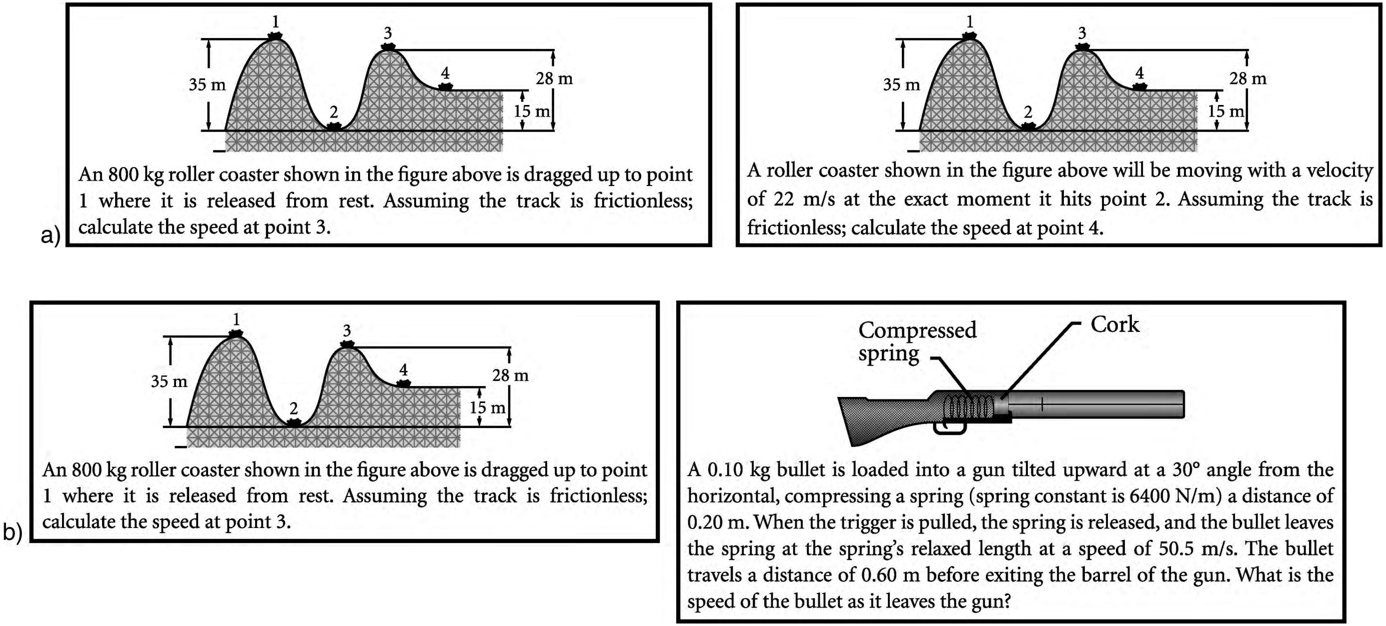
What Are Problem Types and Typologies?

Chapter 15 describes different problem types, each of which is described by a different schema. For example, there are three kinds of simple addition problems: combine, compare, and change. In combine story problems, the quantity is unknown and values must be combined. In a compare problem, the total is known while the student must compare values, and in change problems one of the values must be changed to calculate the total. These are simple problem types; however, larger content domains, such as physics, can contain many different kinds of problems such as Newton's second law, conservation of energy/work-energy, conservation of momentum, angular motion, rotational motion, kinematics, and dynamics, circular motion, center of mass, statics including conservation of angular momentum and work problems, linear kinematics, vectors, and springs.

Instruction should begin with a graphic organizer illustrating each kind of problem solved within the domain and highlighting the problem type currently being solved (see Figure 15.1 [p. 243] for an example of a graphic organizer illustrating the semantic relationships in a combine problem and Figure 15.2 [p. 251] for a semantic map of work-energy problems in physics.) This organizer should explicitly state and contrast the structural differences among problems. Research suggests that learners must be able to classify problems based on structural relationships among the sets in the problem. Emphasizing the structural properties of problems and contrasting them with other problems in the domain enhances learners' abilities to generalize problems within a class and to discriminate between classes. Emphasizing the structural relationships among entities within the problem also focuses the classification on structural properties rather than surface-level, situational characteristics. It is important that learners understand the conceptual nature of the problem and the disciplinary operations represented in the problem. These structural relationships are manifestations of the disciplinary principles that would also be illustrated when this description is accessed.

How Does a Conceptual Model of the Problem Function?

For each problem type in the problem typology, a model of the problem type may be used to describe the structural relationships between the entities in a problem. The conceptual model must also contain a visual model illustrating the situational characteristics of the problem because integrating the structural model with the situational model is necessary. Given that structurally similar problems often contain situationally similar characteristics, the patterns of those relationships must be made explicit. For example, Figure 2.2a displays two problems that are situationally similar (both roller coasters); however, these problems are structurally dissonant (one involves conservative forces and the other non-conservative forces). On the other hand, Figure 2.2b displays a pair of problems that are situationally dissimilar but structurally the same. Students tend to associate problems that are situationally similar (Figure 2.2a) and dissociate those that are situationally dissimilar (Figure 2.2b), even though they are the same kind of problem.



a)

An 800 kg roller coaster shown in the figure above is dragged up to point 1 where it is released from rest. Assuming the track is frictionless; calculate the speed at point 3.

A roller coaster shown in the figure above will be moving with a velocity of 22 m/s at the exact moment it hits point 2. Assuming the track is frictionless; calculate the speed at point 4.

b)

An 800 kg roller coaster shown in the figure above is dragged up to point 1 where it is released from rest. Assuming the track is frictionless; calculate the speed at point 3.

A 0.10 kg bullet is loaded into a gun tilted upward at a 30° angle from the horizontal, compressing a spring (spring constant is 6400 N/m) a distance of 0.20 m. When the trigger is pulled, the spring is released, and the bullet leaves the spring at the spring's relaxed length at a speed of 50.5 m/s. The bullet travels a distance of 0.60 m before exiting the barrel of the gun. What is the speed of the bullet as it leaves the gun?

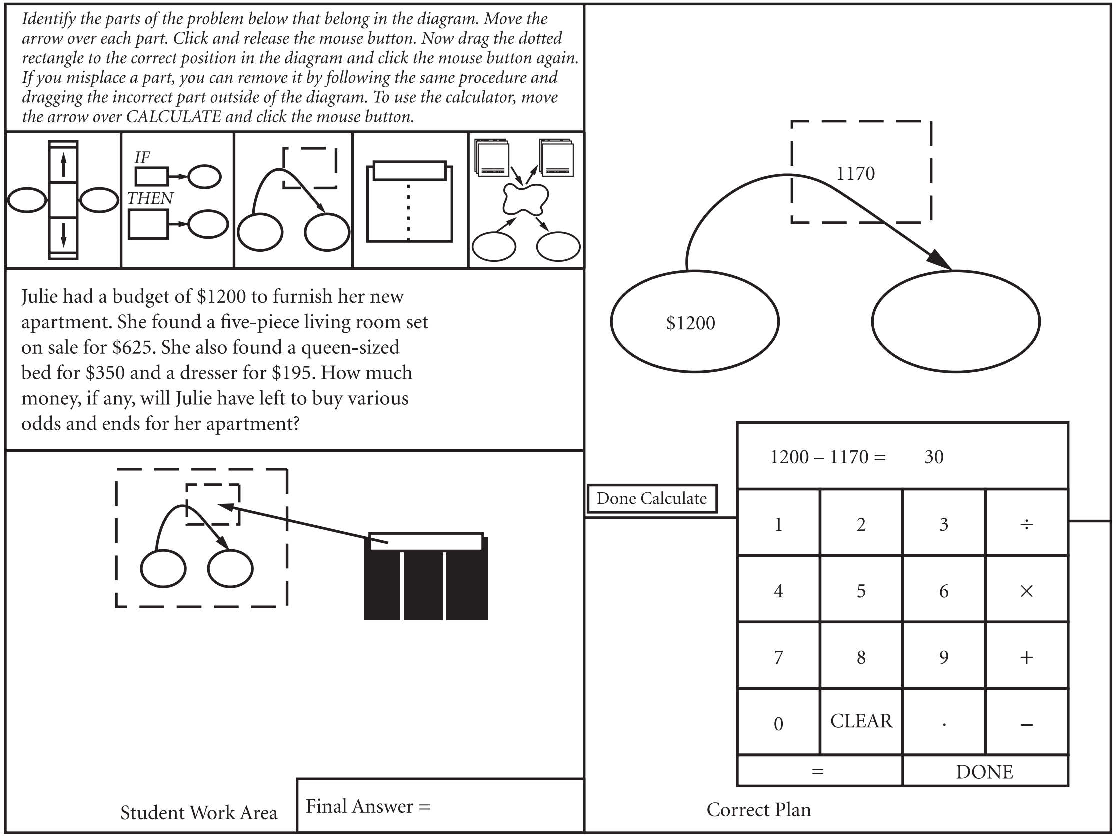
Figure 2.2 (a) Situationally similar, structurally dissimilar problems; (b) situationally dissimilar, structurally similar problems. With permission of Fran Mateycik.

Researchers have developed environments that visually depict the structural relations among problem elements. Marshall argued that in order to learn how to assign sets to an appropriate structural model of the problem, students need methods for structurally representing the problem. Cummins (1991) found that when children drew or selected pictures that represented the problems' structure, solution performance improved, depending on the nature of the pictures drawn or chosen. A crucial determinant was the interpretation that children assigned to certain phrases. Rather than allowing students to select their own problem representations, Marshall (1995) provides a tool for explicitly mapping problem objects and values onto a structural model of the different problem types to scaffold the assignment process.

Marshall's story problem solver (SPS) interface (Figure 2.3) provides users with a small set of conceptually distinct structural models for displaying and solving arithmetic problems (options shown in upper left). These diagrammatic depictions illustrate the different structural relationships involved in different problem types, so each problem type has its own visual depiction. Marshall believed that these visual, structural models (a) represent fundamental relational concepts within a domain; (b) suggest the existence of different problem classes; (c) suggest procedures associated with problem types; and (d) serve as conceptual building blocks for representing complex problems.

The goal of SPS is to help students construct expert math knowledge by having them solve and analyze math story problems using schematic diagrams representing basic structural relationships. In a series of studies, Marshall showed that using her visual diagrams of model types (see Figure 2.3) improved problem classification, recall, and problem performance. Students recalled the diagram and used it to structure recall of problem information. These visual diagrams influence conceptual development by functioning as an anchor for the students' models. When used to represent problem structures, these diagrams should reflect the essential components of the problem structure as simply and uniquely as possible (Marshall, 1995).

A number of computer-based tools for representing story problems have also been tested. ANIMATE is a computer-based tutor that coordinates the situational rather than the structural characteristics of the problem with the equation for solving mathematics problems (Nathan, Kintsch, & Young, 1992). Based on a discourse analysis theory of story problems (Kintsch & Greeno, 1985), ANIMATE runs a simple animation of the problem situation (top of Figure 2.4) that is mapped to a solution-enabling structured equation (bottom right of Figure 2.4).



Identify the parts of the problem below that belong in the diagram. Move the arrow over each part. Click and release the mouse button. Now drag the dotted rectangle to the correct position in the diagram and click the mouse button again. If you misplace a part, you can remove it by following the same procedure and dragging the incorrect part outside of the diagram. To use the calculator, move the arrow over CALCULATE and click the mouse button.

Julie had a budget of $1200 to furnish her new apartment. She found a five-piece living room set on sale for $625. She also found a queen-sized bed for $350 and a dresser for $195. How much money, if any, will Julie have left to buy various odds and ends for her apartment?

1200 – 1170 = 30

Figure 2.3 Problem schema representation in SPS (Marshall, 1995). Reprinted with permission.

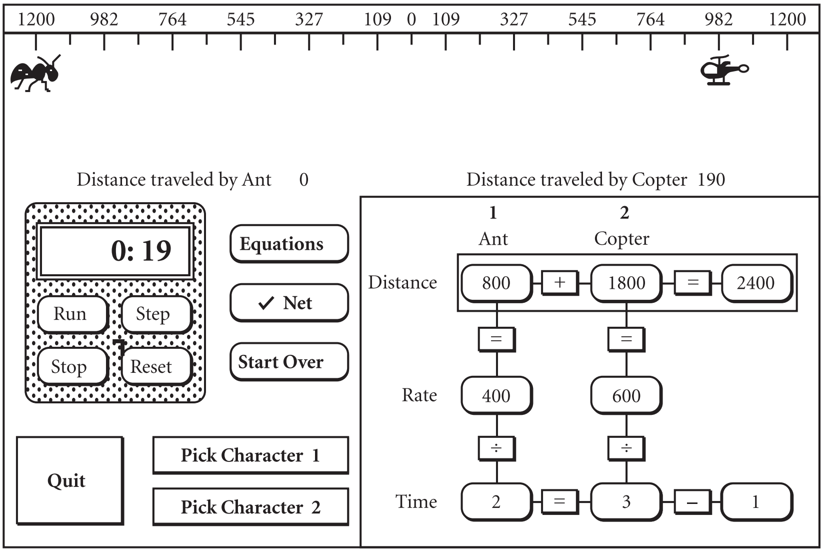


Figure 2.4 Representation of animation and problem structure in ANIMATE (Nathan, Kintsch, & Young, 1992).

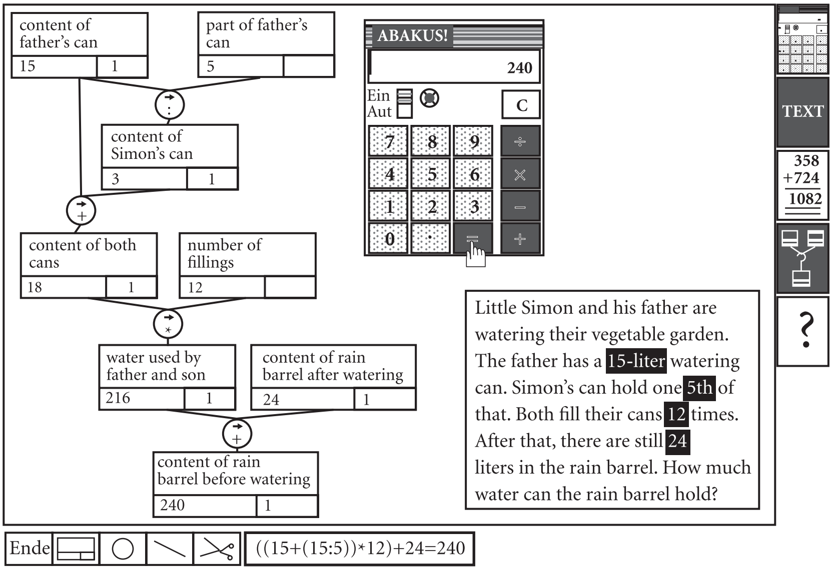
Rather than ignoring situational content, this software intentionally integrates animated situational content as exemplars and feedback. The software was implemented for *amount-per-time rate* problems (Mayer, 1982) using the basic formula $D = R \times T$ (distance D equals rate R multiplied by time T). Learners begin by creating a simulation of the problem by picking characters and selecting the appropriate equation to control their behavior in the animation (see Figure 2.4). Nathan et al. (1992) conducted empirical research that showed that students experiencing ANIMATE outperformed students supported by other environments in recognizing a correct solution, generating equations from texts, and diagnosing errors. Unfortunately, the error correction did not transfer when the environment was removed. The correspondence between the algebraic representation and the simulation was the primary reason for success. ANIMATE did not attempt to integrate the structural and situational characteristics of the problem.

Another method for representing story problems is provided by HERON (Reusser, 1993), a computer-based tool that uses solution trees to conceptualize the structure of mathematical problem solving. Like these other tools, the tree model in HERON is designed to directly mediate the translation of the problem text into an equation without the use of a structural or situational model of the problem. HERON uses a graphical solution (conceptual planning) tree to represent the operation required to solve the problem. Figure 2.5 illustrates a solution tree for representing the following problem:

> Little Simon and his father are watering their vegetable garden. The father has a 15-liter watering can. Simon's can holds one-fifth of that. Both fill their cans twelve times. After that, there are still 24 liters in the rain barrel. How much water can the rain barrel hold?
>
> (Reusser, 1993)

The solution trees, Reusser (1993) argues, are manipulable, dynamic, and flexible means for illustrating the construction process. The objects in HERON solution trees are excellent examples of set schemas arranged to represent the process for solving the problem. They also convey some information about the structural relationships or situation depicted in the problem.

Tutorials in Problem Solving (TiPS) is a more recent conceptually oriented computer environment for training arithmetic and problem-solving skills in remedial adult populations (Derry and the TiPS Research Group, 2001). Students learn to solve change, compare, group, function, and vary problems (Marshall, 1995). TiPS uses worked examples (to be described more fully later in this chapter and in Chapter 9) to present the problem statement and to demonstrate a



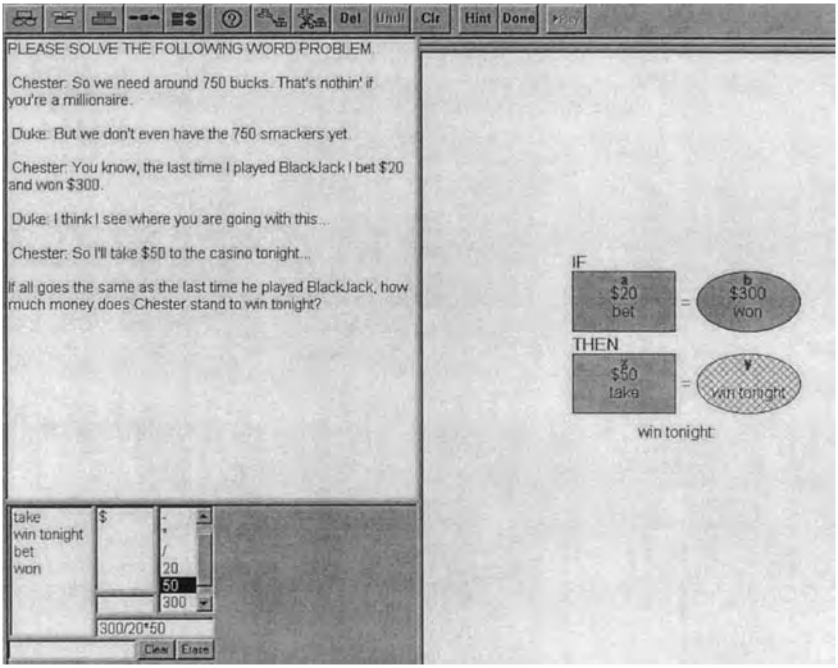
Little Simon and his father are watering their vegetable garden. The father has a 15-liter watering can. Simon's can hold one 5th of that. Both fill their cans 12 times. After that, there are still 24 liters in the rain barrel. How much water can the rain barrel hold?

((15+(15:5))*12)+24=240

Figure 2.5 Solution trees from HERON (Reusser, 1993). Reprinted with permission.

procedure for solving it. Worked examples illustrate how an expert solves the problem for the learner to study and emulate. In TiPS, students use the interface shown in Figure 2.6 to solve the story problems. They read the problem to identify the sets and set relationships in the problem statement. Doing this helps them classify the type of problem and to select the problem diagram that best depicts that problem type (in Figure 2.5, a restate problem). Students drag the diagram onto the screen and fill it in by dragging and dropping words from the problem statement into appropriate cells in the diagram. When this structural mapping process is complete, students construct an arithmetic formula to calculate the solution.

Although TiPS uses a Bayesian student model to adapt instruction and feedback, its more important feature is the problem representation formalism that it uses. Derry and the TiPS Research Group (2001) conducted a pair of experiments on the interface. In the first experiment, they compared the TiPS interface with a hierarchical solution tree similar to those in HERON (described previously). Students using the TiPS interface performed better than those using solution trees,



PLEASE SOLVE THE FOLLOWING WORD PROBLEM.

Chester: So we need around 750 bucks. That's nothin' if you're a millionaire.

Duke: But we don't even have the 750 smackers yet.

Chester: You know, the last time I played BlackJack I bet $20 and won $300.

Duke: I think I see where you are going with this...

Chester: So I'll take $50 to the casino tonight...

If all goes the same as the last time he played BlackJack, how much money does Chester stand to win tonight?

300/20*50

Figure 2.6 TiPS interface for representing and solving simple mathematics problems. Derry and the TiPS Research Group (2001). With permission of Sharon Derry, University of Wisconsin.

especially among lower-ability students. In the second experiment, some remedial adult learners used the TiPS schema interface while others used an interface design based on a heuristic problem-solving model that guided student practice. Students using the TiPS schema interface made greater gains over time. It appears that among adult remedial learners, the TiPS interface provided a performance advantage.

Contemporary research on story problems confirms the importance of constructing a conceptual model of the problem prior to solving it. The research by Marshall (1995) and Derry and the TiPS Research Group (2001) focused on using structural models of problem types to help learners classify and parse story problems. Nathan (1998) focused on the situational model of the problems, and Reusser (1993) concentrated on the solution process. The proposed model for solving story problems being described in this chapter is unique in its integration of structural and situational models of the problem with the processing operations. Because the most successful story problem solvers are those who can integrate the situational and structural characteristics of the story problems, it is essential to support the association of these elements.

How Are Worked Examples Used for Story Problems?

Research by Sweller and his colleagues have investigated a method for teaching story problem solving that emphasizes the use of worked examples. Worked examples of problem solutions that precede practice facilitate practice-based problem solving by helping learners to construct problem schemas (Cooper & Sweller, 1987; Sweller & Cooper, 1985). Unfortunately, the problem schemas that students construct often include only procedural models of how to solve the problem but not what the problem means, because worked examples generally emphasize only processing steps (see Chapter 9 for more detail on worked examples). When using worked examples, however, Atkinson, Derry, Renkl, and Wortham (2000) verified a number of instructional design principles such as providing multiple examples per problem type in multiple forms that feature structural components. Examples should integrate parts, use multiple modalities, and clarify the structure of subgoals. This process is afforded and supported by the story-problem learning environment described next. The worked examples of problems must emphasize each of the processes for parsing the verbal problem representation, categorizing the problem type using the conceptual model, mapping problem sets onto the situational model and the structural model, mapping the structural model onto a formula, estimating the size and units of the outcome, solving for the goal, and reconciling the outcome with the estimate (as described in Figure 2.1). A brief description of these follows in Figure 2.6.

The first subgoal of the problem-solving process is to parse the problem presentation (usually verbal, perhaps with an illustration). The most important part of the parsing process is the assignment of the elements in the problem to set schemas. A set schema contains slots for the objects in the problem, including the quantity of the object (e.g., number, some, how many), specification of the object that distinguishes it from other objects (e.g., owner, location, time), and the way the object is related to other objects (sets) (e.g., start, transfer, result, superset, largest, smallest, etc.) (Kintsch & Greeno, 1985). Those sets are also illustrated in the HERON environment in Figure 2.5. HERON identifies sets and shows how they are combined or manipulated to solve the problem. Ensuring that learners identify each of the sets required to solve the problem is prerequisite to any other kind of modeling, so the process must be modeled in the worked examples. It is also important that learners distinguish between the sets required to solve the problem and those included in the problem as distracters. Another characteristic of the story-problem learning environment that I am describing is the identification of sets and the mapping of those sets onto the structural model. (See Figure 15.2 [p. 251] for an example of a structural model of a work–energy problem.)

The second subgoal in the worked example is the problem classification. This entails analyzing the situational and structural components of the problem and matching them to the situational and structural components of the problem types. This attribute-matching strategy is the most commonly used strategy for learning concepts (Merrill & Tennyson, 1977). An alternative approach is suggested by Mestre, Dufresne, Gerace, and Hardiman (1993), who developed a decision tree/expert system job aid for helping learners to classify physics problems called the hierarchical analysis tool (HAT). When queried, HAT asks learners a series of conceptual questions about the physics principle being applied (angular momentum, Newton's second law, work and energy, etc.); the changes to mechanical, kinetic, and potential energy; and the boundary conditions of the problem. HAT then yields the correct formula, assuming that the learner has answered questions correctly. This computer-based coaching system improved problem-solving performance but did not show any effects for problem classification, an essential outcome of problem schema construction. Perhaps that is because the questions were generated from a tree structure rather than a more conceptual model of the problem. In the story-problem learning environment, the structural model is used as the basis for classifying problem types.

How many worked examples are necessary, and how difficult do they need to be? Clearly, a single example is insufficient. Based on the weaknesses of single analogies, Gick and Holyoak (1983) found that two examples facilitated transfer of the concepts that were impossible with a single one. Reed and Bolstad (1991) found that the most consistently high performance across near and far transfer algebra problems resulted from showing a simple and then a complex worked example. As the problem elements were changed in practice problems to require more mental transformations, it was found that solvers experienced less cognitive load than with a single examples or examples supported by a description of procedures. There is no definitive research on this question; however, a reasonable recommendation is to provide three worked examples, the first a simple problem, another with a more complex problem, and a third with a transfer problem (i.e. one that entails transformations or changes in context).

How Are Practice Items Used for Story Problems?

Another essential component of any story problem-solving learning environment is the opportunity to practice the skills acquired in the environment. Practice problems should be presented to students in the form illustrated in the worked examples and similar to the form in assessment. Students would use the same environment to practice solving problems that was used in the worked examples. Students are fairly successful in matching practice problems with the examples, preferring the complex example as a model (Reed, Willis, & Guarino, 1994). Similarly, students should be allowed to use the environment that was used in the worked example to scaffold their practice performance until they are competent. If the assessment process does not allow the students to use the environment when solving the assessment problems, then it is necessary to fade the use of the scaffold. That is, after students are able to competently solve problems with the scaffold, require them to begin to represent and solve problems in the absence of the scaffold until they are able to perform competently without it.

Feedback on problem-solution efforts may be summative or formative. Summative, knowledge-of-correct-response feedback is presented at the end of the problem-solution process. The student parses the story problem and uses the learning environment to represent and solve the problem and receives feedback on the accuracy of the answer. This is the easiest form of feedback to provide. Additionally, students may receive formative feedback during the problem-solution process. If students identify the correct problem type, identify and place the correct problem sets into the correct problem representations or make reasonable problem-solution estimates, they can receive feedback about any of these activities. Such feedback can also represent a scaffold that can and should be faded before the learning process is deemed complete. A powerful form of feedback was provided in the ANIMATE environment (Nathan et al., 1992) where the values and operators that students identify in the problem are used to drive a situational animation of the problem. Students provided with situation-based animations made greater gains in problem-solving skills than students provided with knowledge-based feedback (Nathan, 1998). This type of feedback was implemented for only one kind of problem (distance/rate/time).

Given the large numbers of classes of problems in different domains and the vast numbers of situational contexts in which those problems could be embedded makes animation a problematic strategy from a practical perspective. The nature and scheduling of feedback with story problem-solving environments represents an important area of research with many potential research questions.

WHAT ARE THE COMPONENTS OF A STORY-PROBLEM LEARNING ENVIRONMENT?

In this section, I illustrate a model for a story-problem learning environment (see Figure 2.7). The focus of the environment is the current story problem that the student is trying to solve. Students are provided with a situational model as well as a structural model of each kind of problem to assist in classifying the kind of problem being solved. Additionally, instruction on the kind of problem is available at the moment of need. Students are also provided with analogous problems (see Chapter 11) to which they may analogically compare to the current problem to solve (see Chapter 16 for a detailed description of the analogical encoding process). Students are provided with a set identifier to help them to parse the problem as well as an equation builder and calculator to help them to generate and solve an appropriate equation to represent the problem.

The environment is exemplified with physics problems in Figure 2.8 and 2.9. As the physics problem types and structures differ, so too do the situational and structural characteristics represented in the environment. The physics-problem learning environment illustrated in Figures 2.8 and 2.9 functions as a cognitive tool (Lajoie & Derry, 1993) for representing and manipulating problem components tied to a conceptual model.

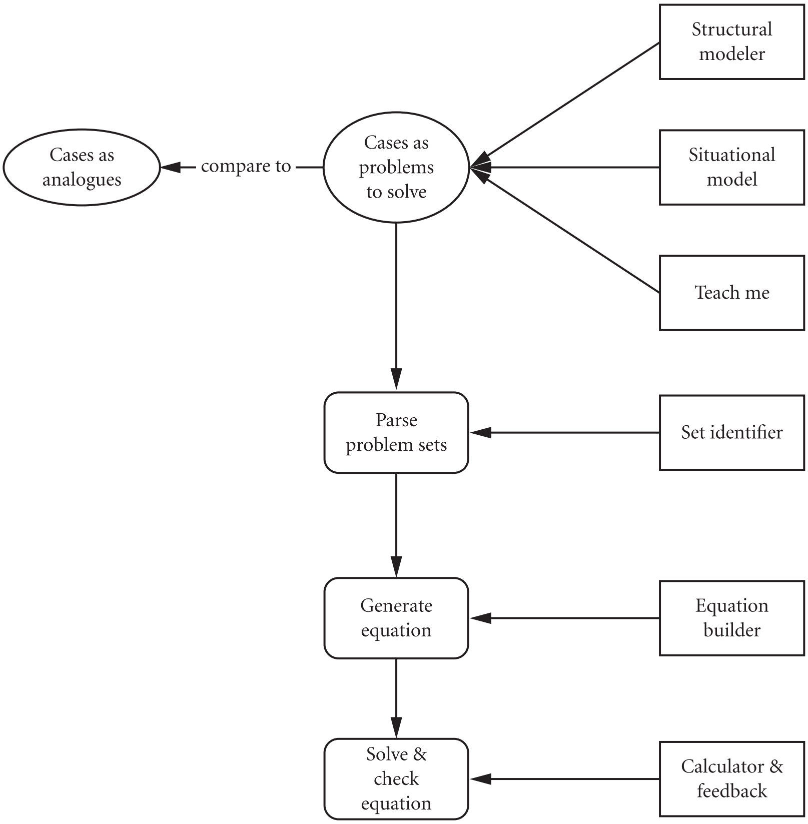
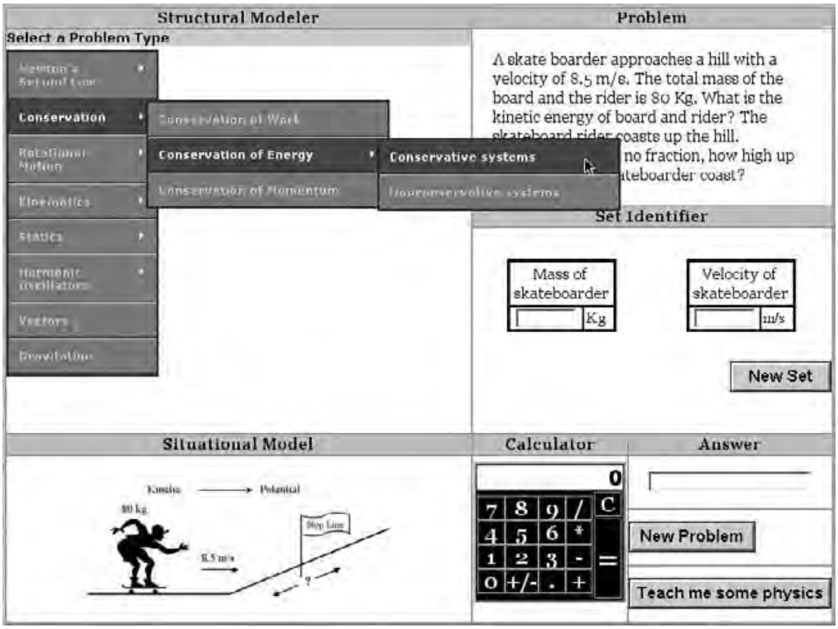


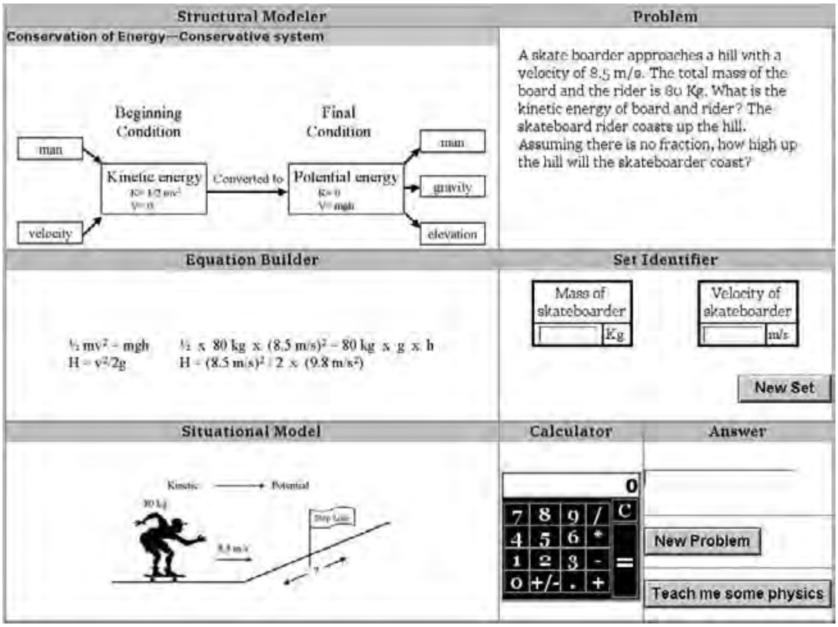
Figure 2.7 Model for story problem learning environments.

The verbal problem in the story-problem learning environment is presented in the upper right-hand corner of the screen shot in Figure 2.8. The student first uses the pull-down menu shown in Figure 2.8 to classify the problem. Double clicking on any class displays a structural model of the problem (that shows up in Figure 2.9), examples of the same problem class, and conceptual instruction of the underlying physics principles if the student chooses. The student correctly classifies this problem as a simple conservation of energy problem. The student then uses the set identifier to assign entities from the problem to set schemas. To use the set identifier, the student clicks on "New Set." A set schema consists of three smaller boxes. The top box identifies the object and the lower boxes in each set box identify the quantity and the units describing the object. The student highlights objects and values from the story problem and drags and drops them into sets. Two sets have been identified in Figure 2.8 (the mass of the skateboarder and the velocity



A skate boarder approaches a hill with a velocity of 8.5 m/s. The total mass of the board and the rider is 80 Kg. What is the kinetic energy of board and rider? The skateboard rider coasts up the hill. … no fraction, how high up …ateboarder coast?

Figure 2.8 Example of story problem architecture selecting structural model.



A skate boarder approaches a hill with a velocity of 8.5 m/s. The total mass of the board and the rider is 80 Kg. What is the kinetic energy of board and rider? The skateboard rider coasts up the hill. Assuming there is no fraction, how high up the hill will the skateboarder coast?

$\frac{1}{2} mv^2 = mgh$ $\quad$ $\frac{1}{2} \times 80\ \text{kg} \times (8.5\ \text{m/s})^2 = 80\ \text{kg} \times g \times h$

$H = v^2/2g$ $\quad$ $H = (8.5\ \text{m/s})^2 / 2 \times (9.8\ \text{m/s}^2)$

Figure 2.9 Example of story problem architecture with structural model.

of skateboarder). One of them is the primary object needed to solve this problem.

Students then use the structural modeler (Figure 2.8, upper left) to assign sets to the structural model. The student begins by pulling down a menu to select the type of problem being solved (in this case a conservation of energy problem in a conservative [frictionless] system). Selecting that problem type results in a structural model of that problem type appearing in the structural modeler space (Figure 2.9). The model describes the structural components of the problem. Students drag and drop the sets from the set identifier into the components of the structural modeler. In this problem, the student needs to identify the initial energy conditions (kinetic and potential) and the ending energy conditions (kinetic and potential). In the initial conditions, potential energy is 0 and kinetic is determined by calculating $1/2mv^2$. So the student drags the mass and velocity sets into the structural modeler. In the ending condition, kinetic energy is 0 (skateboard stops), and potential energy is determined by calculating *mgh*.

From the structural model, students assign values to an equation using the equation builder (Figure 2.9). To use the equation builder, the student drags the formulas from the structural model into the equation space, cancels out and reorganizes the variables, and uses the calculator to apply the formula. The situational model is a visual depiction of the context. The situational model helps learners to relate the problem structure to a real-world context. Being able to compare and contrast the situational and structural models provides a richer mental model of the problem type. An animated version of the situational model may provide explanatory power but inevitably result in greater costs. Instruction consists of worked examples using this environment to illustrate how to solve at least three problems for each problem type before allowing students to practice. In a face-to-face environment, the teacher would work through these examples. In a technology-supported environment, an animated lifelike pedagogical agent (Lester, Stone, & Stelling, 1999) can be used to work through the examples. The agent first reads the verbal problem representation in the story-problem learning environment, looking for clues to help to classify the problem type (in our example, conservation of energy in a conservative system). The agent then selects that problem type. According to the resulting structural model, the agent must find the initial and final energy conditions. Returning to the problem, the agent begins to identify the sets required for the problem, to move those sets onto the structural model, and then to map those values into a formula in the equation builder. The agent performs a unit check and then estimates the size of the answer. The agent then solves for the answer and reconciles the outcome with the estimate. Performing this demonstration with two other more complex problems prepares the student for completing practice items. At any time in the worked example or practice phases the student can elect to have the agent teach some physics by clicking on the "Teach Me Some Physics" button that provides conceptual instruction on the problem type. The agent presents conceptual instruction on the nature of the problems, the entities involved, and their physical relationships to each other. We are seeking support to investigate the efficacy of this environment.

HOW DO WE ASSESS STORY PROBLEM SOLVING?

Assessing learners' problem-solving skills is a necessary part of any learning process. The following kinds of assessment should be considered when assessing story problem-solving skills.

How Do We Assess Problem-Solving Transfer?

One form of assessment is problem-solving transfer. Near-transfer tests provide new problems at the same level of complexity using the same problem contexts that were used in the learning environment. Far transfer can be assessed by providing structurally similar problems in new contexts (i.e. contexts different from those used in the environment) and increasing problem complexity. Problem complexity is increased by adding more factors, restating those factors in relative rather than absolute values, or by requiring transformations. Transformations in work problems ("Ann can type a manuscript in ten hours and Florence can type it in five hours. How long will it take if they work together?"), for instance, are affected by changing either the rate, the time, or the task (Reed & Bolstad, 1991). A change in rate, for example, may involve expressing the rate of a worker relative to the other worker, rather than as a value. A time change may involve one worker working longer than another or the time worked stated as a proportion of the other worker's time. A task change might occur when part of the task was completed earlier. Transformations can be combined in a problem. Beware because, regardless of the form of instruction, performance decrements increase with the number of transformations in a problem (Reed & Bolstad, 1991).

Assessing conceptual understanding can be accomplished using a variety of methods (see Chapter 22), such as text editing, problem classification and problem similarity. To assess students' understanding of the kind of problem being posed, you can ask questions about structural relationships among the problem elements, especially the causal relationships. You can also use problem classification and text editing. All of these methods are described in Chapter 15. Additionally, you can ask students to argue for their solutions or to argue for the correct solution if they should not solve the problem correctly (see Chapter 20 on argumentation for more detail). If your goal is to improve students' semantic understanding of problem types, then it is essential that you provide one or more of these alternative semantic assessments If you ask students to only solve problems quantitatively, then they will not focus attention on the semantic attributes of the problem and will continue to use the traditional direct translation strategy for solving the problem. The result: they will miss the physics.

3

DECISION-MAKING PROBLEMS

WHY STUDY DECISION MAKING?

Decision making is the most common form of problem solving in our everyday lives. We make countless decisions every day, many without conscious awareness. For example, navigating from your car to the office requires numerous decisions about the route, elevator strategies, and interpersonal interactions. (Should I say “Hi” to that person or pretend I did not see him?) We constantly make decisions in our everyday lives and our professional lives, such as:

- What should I wear to work today?
- Should I move in order to take another job?
- Which benefits package should I select?
- Should I have surgery or try a drug regimen?
- Which automobile should I purchase to meet my needs?
- What will be the most efficient route to work at this hour?
- What will I select to eat from this menu?
- Which candidate(s) should I vote for?
- Should I purchase an extended warranty for my new appliance or car?

In our professional lives, we constantly make decisions, such as:

- Determining guilt or innocence of a defendant in a criminal trial;
- Selecting people for employment or organizational membership;
- Selecting the best material for manufacturing industrial parts;

- Selecting a treatment option for a medical patient;
- Selecting the most effective marketing strategy for our new products;
- Selecting the most effective insurance plan;
- Deciding on proportions of banties, guineas, and turkins in my poultry operation;
- Selecting stocks for an investment portfolio;
- Selecting a new appellate judge.

Essentially, decision making involves the selection of one or more beneficial or satisfying options from a larger set of options. Those options may consist of requirements, strategies, events, predictions, and opportunities, but the decision always requires “a commitment to a course of action that is intended to yield results that are satisfying for specified individuals” (Yates, 2003, p. 24). According to Yates and Tschirhart, (2006), there are many different kinds of decisions, including:

- **Choices**: where you select a subset from a larger set of alternatives (e.g., dinner options from a menu, clothes purchased from department store, automobiles to purchase from a car lot);
- **Acceptances/rejections**: a binary choice in which only one specific option is acknowledged and must be accepted or not (admission to graduate school, acceptance by a country club, issuance of automobile driver’s license);
- **Evaluations**: statements of worth that are backed up with commitments to act (e.g., bid on a house, assignment of grade in a course, proposal for new courthouse building);
- **Constructions**: attempts to create ideal solutions given available resources (e.g., budget plan for fighting a fire).

Decisions, regardless of kind, include the following features (Yates & Tschirhart, 2006):

- **Action**: Action is taken by the decision maker, typically involving a selection.
- **Commitment**: Decisions are made as soon as there is a commitment to act.
- **Intention**: Decisions are driven by a purpose or intention (usually thought to be optimization of value, benefit, or utility).
- **Satisfying results**: Decisions that provide the greatest utility are the most satisfying.
- **Specified individuals**: Decisions are made for someone by someone.

We all usually hope to make optimal decisions for ourselves and for others. Parents make decisions about school options, health care, and social activities for their children, who are hopefully the beneficiaries of their decision making. Every day is replete with decisions of minor and major importance. If decision making is the most common kind of problem solved in our everyday and professional lives, then we need to better understand the processes involved and to develop methods and strategies of instruction that support coherent decision making. That is the purpose of this chapter.

HOW DOES DECISION MAKING RELATE TO OTHER PROBLEMS?

Another important reason for studying and supporting decision making is the centrality of decision making to more complex kinds of problem solving. In Chapter 1, I articulated a typology of problems that includes algorithms, story problems, rule-using/rule-induction problems, decision-making problems, troubleshooting, diagnosis-solutions problems, strategic performance problems, policy-analysis problems, design problems, and dilemmas, many of which are described more fully in Part I of this book. The underlying assumption of that typology is that as the nature of problems varies, the nature of the thinking and activity required to solve those problems varies. That is, one does not solve a medical-diagnosis problem the same way that an engineer designs a piece of medical equipment. To some degree, each kind of problem calls on a distinct set of cognitive skills and processes in order to solve it. Although the typology of problems was not intended originally to imply taxonomic relationships, I believe that there exists a taxonomic relationship among some kinds of problems.

As described in Figure 3.1, many kinds of problems (e.g., policy analysis, diagnosis, and design problems) integrate decision making into those more complex kinds of problem-solving processes. That is, these more complex kinds of problem solving may be conceived of as a series of decision-making problems. Decision making is a critical component within more complex problems such as diagnosis, negotiation, design, situation assessment, and command and control (Means, Salas, Crandall, & Jacobs, 1993). Although some problems require only decision making (e.g., what kind of insurance policy should I select), other more complex problems entail sequential or iterative decision-making processes. For example, Chapter 7 describes design problem solving as an iterative process of decision-making and model building. "The principal role of the designer is to make decisions. Decisions help to

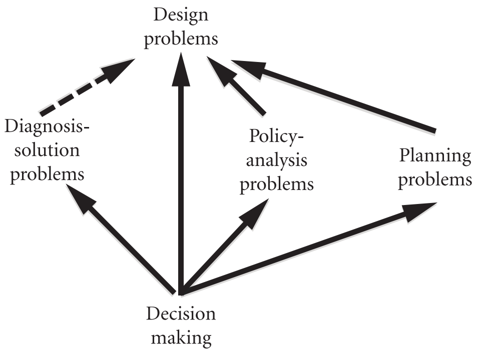


Figure 3.1 Taxonomic (prerequisite/corequisite) relationship among problems.

bridge the gaps between idea and reality, decisions serve as markers to identify the progression of the design from initiation to implementation to termination" (Marston & Mistree, 1997, p. 1). Design is an iterative process of decision-making. After articulating an initial set of constraints and functional specifications, designers make decisions about the object or process being designed (materials, functionality, style, medium, etc.). Those decisions are influenced by emergent constraints and beliefs. With each cycle, the number and complexity of decisions reduce to a point that satisfices the need (Simon, 1957). As design decisions are made, degrees of freedom decrease as the designer approaches the final solution.

HOW ARE DECISIONS SUPPOSED TO BE MADE?

Historically, there have been two basic approaches to studying decision making: how decisions should be made and how decisions are, in fact, made (Skinner, 1999). The former approach is based on prescriptive or normative theories or models of decision making, while the latter represent descriptive theories, sometimes referred to as naturalistic decision making. Normative theories of decision making attempt to identify the optimal choice in any situation under uncertainty. Those theories provide the basis for operations research and decision-theory research. The research in normative theories of decision making examines how people make decisions involving risk or rational choice under different theoretical constraints. That research has sought to develop theories about how rational, informed people ought to identify the best option, the study of which is usually based on statistical analysis of options. The goal, as described earlier, is to maximize expected value by evaluating options with different probabilities that will result from each course of action.

There are two different kinds of normative models of decision making. In these decision-making problems, a limited set of alternative actions or solutions (e.g., which car should we buy; which monetary instruments should we invest in; which health plan do we select?) are presented. The first is a formal-empiricist model in which decision makers probabilistically analyze options and make the choice that reduces risk or loss or maximizes expected value. This kind of decision normally assumes a gambling metaphor, where the decision maker determines the level of acceptable risk with regard to potential payoffs (Beach & Connelly, 2005).

The other kind of normative theory of decision making assumes that decision makers generate options, determine evaluation criteria, evaluate each option in terms of the criteria, calculate weights, and select an alternative based on weighted criteria. This multi-attribute theory of decision making assumes that people rationally analyze decision options in order to maximize expected value. Both approaches have been shown to be unsuccessful, because a one-size-fits-all strategy often fails in specific settings (Klein, 1997) and because they explicitly ignore domain knowledge. Newer conceptions of decision-making, such as naturalistic decision making (Zsambok & Klein, 1997), examine how experienced people make decisions in contextually rich situations. I shall explore each of these conceptions because they each provide different perspectives on the decision-making process. Those perspectives may be useful in helping naive learners to develop more sophisticated decision making skills.

How Do People Gamble on Decisions?

Modern theories of decision making emerged from analyzing games of chance rather than a psychological analysis of risk or value (Tversky & Kahneman, 2000). The probabilistic analysis of different options resulted in research that assumed a gambling metaphor, leading to normative theories of decision making focused on maximizing the expected value from any gamble. The most commonly researched approach to decision making conceives of decision making as risk assessment where people assess the probability of avoiding risk or a process of cost–benefit analysis, where people assess the likelihood of deriving the biggest benefit from any decision. This research employed laboratory studies where subjects were asked to choose between risk alternatives. The most common experiments employed gambling as a metaphor (e.g., lotteries), such as: If you were given a choice, which gamble would you bet on:

- **Choice A**: A 10% chance of making $100,000 and a 90% chance of making nothing.
- **Choice B**: A 30% chance of making $50,000 and 70% of making nothing.

However, other risk assessment scenarios were used to test subjects' choices under uncertainty. For example, selecting between alternative therapies for tumors (radical treatments or moderate treatments):

- **Treatment A**: A 20% chance of imminent death and 80% chance of normal life, with an expected longevity of thirty-five years.
- **Treatment B**: Certainty of normal life, with an expected longevity of eighteen years.

(Tversky & Kahnemen, 2000, p. 217)

The assumption of this research paradigm is that people seek to maximize the expected value or utility from any decision, so the best decisions are those that maximize the benefit to the decision maker. Utility is determined by a simple formula: probability of each option times the value of each option. The option with the highest expected utility or value would be chosen by any rational person.

Decisions are always made under uncertainty and risk (Huber, 1995). Each alternative has consequences. Whether a consequence occurs is not in the hands of the decision maker but depends on chance, nature, and luck. Decision makers are supposed to calculate which option will produce the greatest expected value or utility. Although many researchers have challenged the assumptions of gambling decisions (discussed later), many decisions (e.g., financial, political, military) do involve some risk, so helping learners to assess and accommodate that risk in their decisions may be useful. Huber (1995) has proposed a model of risk assessment that includes the following steps:

1. Mentally represent the structure of the system (identify variables and relationships among them; e.g., in an investment task, capital is the target variable).
2. Determine goals for target variables (which value or set of values should the target variables reach?).
3. Choose betting strategy for reaching target variable (e.g., if probability of winning is less than 50%, then bet very low).
4. Make choice of stake (amount invested or bet based on perceived risk).
5. Planning and control (evaluation of betting strategies).

Safir (1993) identified a couple of important but tacit gambling strategies. He found that positive dimensions are weighted more heavily when choosing rather than rejecting; negative dimensions are weighted more heavily when rejecting than choosing; and enriched options tend to be chosen and rejected more than impoverished options. While the probabilistic approach to decision making has critics, models such as this do convey the probabilistic nature of uncertainty that does surround many decisions.

How Do People Make Rational Decisions in Everyday and Professional Situations?

The other prominent normative theory of decision making describes alternative methods for making tradeoffs among different goals that are implicit in the options in order to increase expected utility or value. Referred to as multi-attribute utility theory or rational choice, this normative method is about comparing values of different options and rationally selecting the option that accumulates the highest number of points. Numerous rational choice models have been promoted. The method described by Soelberg (1967) includes the following steps:

1. Identify the set of options.
2. Identify the ways or criteria for evaluating the options.
3. Weigh each evaluation dimension.
4. Rate the options.
5. Select option with highest score.

Janis and Mann (1977) elaborated that process slightly by addressing possible risks:

1. Thoroughly canvas a wide range of options.
2. Survey the full range of objectives.
3. Carefully weigh the costs, risks, and benefits of each option.
4. Intensively search for more information in evaluating options.
5. Assimilate all information.
6. Re-examine positive and negative consequences of each option.
7. Carefully plan to include contingencies if various risks occur.

Rational-choice models of decision making were not intended to be used in time-pressured situations. Rather, decisions under pressure are described by naturalistic decision-making models (see Chapter 5). Rational-choice methods rely on quantitative analysis (assigning weights and summing weighted options), so they are deemed objective and rigorous, resulting in reliable decisions (Klein, 1999). They are also deemed comprehensive because they help novices determine what they do not know, and they can be used in a wide range of situations. Therefore, rational-choice methods are more likely to be used when there is a need for justification, or in conflict-resolution situations where optimization is sought (Klein, 1998).

Given the implicit logic of expected utility theory, who can argue with such a rational approach? Over several decades of research, a number of paradoxical research findings have called into question how rational people really are. People often make choices that defy rationality, preferring options with lesser value but greater certainty (Plous, 1993). Often, when multiple options are presented in pairs, people do not ascribe value to each option consistently. "There is little doubt that people violate the principles of expected utility theory" (Plous, 1993, p. 95) because information about alternatives is missing, perception is selective, and memory is fraught with biases. Most of the research on expected utility was conducted in laboratory settings with topics that were isolated from reality. When decisions relate to things that really matter among people, they often violate rules of rationality, illustrating once again that motivation and cognition are integrally related.

Decision theorists and analysts have developed a variety of tools to assist in rational decision making. I review only a few that may help novices to undertake more complex decision making.

How Do You Use a Decision Matrix to Make Decisions?

Perhaps the most common decision-making aid is the decision matrix (aka Pugh method) where options are described in rows and criteria based on quantitative or qualitative values (e.g., urgency, cost, effort or time, buy-in, difficulty, etc.) are displayed in columns in a matrix or table (see Table 3.1). For example, if a person were using a decision matrix to select a new car for purchase, the options would be listed in the left column (e.g., Ford Model A, Honda Model B, Toyota Model C,

Table 3.1
Decision matrix

	Criterion 1	Criterion 2	. . .	Criterion N
Option A	Value A1	Value A2	. . .	Value AN
Option B	Value B1	Value B2	. . .	Value BN
. . .	. . .	. . .	. . .	
Option N	Value N1	Value N2	. . .	Value NN

etc.). Criteria that are critical to the decision might include fuel economy, reliability estimates from consumer reports, hauling capacity, sexiness, and whatever other qualitative or quantitative assessments can be made. Each column is weighted in terms of importance. For example, fuel economy might be the most important factor and therefore weighted 40%. Each optional decision is rated in terms of each criterion, with the winner being the option with the highest weighted score.

Decision matrices are most commonly used when a single option must be selected from a list of options, often described by multiple criteria. For example, only one car can be afforded, or one new marketing plan implemented. While rational methods, such as decision matrices, have been criticized, they can prove useful for novice learners who possess under-developed mental models about the decisions being made. For example, Jonassen, Tessmer, and Hannum (1999) showed how a decision matrix may be used during analysis phase of design to select the most important shipboard training needs (Table 3.2).

We are currently designing and evaluating a problem-based learning version of a basic materials science course in the mechanical-engineering curriculum. Rather than teaching students about materials, students are presented with decision-making problems (e.g., You have been asked to redesign X-ray film cassettes so that they are lighter but retain the same stiffness to bending loads), and they must make decisions about the most appropriate material and materials processing required to fulfill the task. We will scaffold students in the first part of the course with decision matrices that include some of the properties in Table 3.3 when comparing alternative materials. Decision matrices are useful for helping novices to rationally evaluate decision options.

How Do You Use a Swot Analysis to Make Decisions?

Another popular business-oriented decision-analysis tool is known as SWOT analysis. SWOT analysis is a two-dimensional analysis that examines both internal and external forces operating on the business that are both positive and negative. The internal forces consist of strengths and weaknesses of the organization, while the external forces describe opportunities and threats to the organization. During a SWOT analysis, the decision makers will ask what the strengths of the business are (What strengths do we have? What resources do we have available?) while also examining internal weaknesses (What weaknesses do we have in process or organization? What weaknesses do others perceive

Table 3.2
Decision matrix for selecting tasks for analysis (Jonassen, Tessmer, & Hannum, 1999)

Task Selection Criteria Worksheet

Tasks	Criticality (40)	Universality (10)	Standardization	Feasibility	Difficulty	Total	Notes	Priority
Swab the deck	0	10	2	10	0	22		6
Load machine x	30	2	9	9	0	50	Error element of operation	5
Recharge CO_2 fire extinguisher	30	5	10	9	0	54		4
Extinguish a fire	40	6	8	6	15	75		3
Identify a threat contact	40	2	10	8	24	84		2
Fire a ballistic missile	40	3	10	8	3	91		1

Table 3.3
Materials properties to be used in decision matrix in materials science

Mechanical Properties	Physical Properties
Young's modulus (d)	Melting temperature
Poisson's ratio (d1)	Density
Yield and tensile strength (d1)	Thermal conductivity
Shear modulus (d)	Specific heat
Shear strength (d)	Electrical conductivity
Hardness (d2)	Glass transition temperature
Ductility (d1)	
Work hardening exponent (d)	
Damping ability (d)	
Fatigue & Fracture Properties	**Other Properties**
Fatigue strength (f3)	Hardenability (i3)
Crack growth rate (f2)	Processability (d, e, h, i)
Fracture toughness (f1)	Price
Creep strength (f3)	Recyclability
Impact energy (f)	Life cycle energy consumption
Ductile to brittle transition (f)	

we have?). SWOT analysts will also examine external forces, including opportunities (What situations can we capitalize on?) and threats to our ability to address those opportunities (What obstacles will impede progress?). Examples of SWOT options for business expansion include:

- **Strengths:** name-brand recognition, financial stability, existing patents or copyrights, diversified product line, strong corporate leadership;
- **Weaknesses:** lack of diversification, poor financial stability, high turnover, poor leadership;
- **Opportunities:** partnerships, emerging markets, emerging customer bases, strong economy, new markets, new technologies;
- **Threats:** laws and regulations, weak economy, increased competition, weak labor markets, supply problems.

Conducting a SWOT analysis should enlighten most decisions.

How Do You Use Expert Systems?

A common method for representing procedural knowledge is a production-rule system, which consists of facts and rules in the form: IF (condition/expression), THEN (action/expression). Based on extensive work with intelligent tutors, Anderson (1993) argued persuasively for the use of production-rule systems for representing cognitive skills, such as decision making. Production-rule systems have traditionally been built in artificial-intelligence languages such as LISP or Prolog; however, a variety of expert system editors for constructing production-rule knowledge bases are now commonly available. In order to build an expert system, you need to identify the goals, decisions, or outcomes of the knowledge base. Next, you identify the decision factors in the form of questions that will be asked of the user. This is really the essence of the design process. Writing questions that are simple enough for any novice user to be able to answer is difficult. The designer then constructs the rules using Boolean logic to relate the decisions or conclusions to the factors or questions already specified. Table 3.4 illustrates a simple rule base for selecting the most appropriate statistical test to use when analyzing different data sets. Expert system rule bases may be constructed by knowledge engineers to guide novice students through decision-making processes. However, such advice should not be accepted uncritically. In the case of expert systems and intelligent tutors, many of the more expansive claims about their cost-effectiveness have been shown to be unfounded. Also, at the theoretical level, there are some important tradeoffs in the various knowledge structure representations these methods use. Understanding these tradeoffs is a key state-of-the-art question.

My strong preference is to have learners construct their own expert systems to describe the decision-making process. This latter activity is an example of using expert systems as Mindtools (Jonassen, 2006a), where students construct their own models of cognitive processes, a much more engaging activity. The use of tools, such as expert systems, is described in Chapter 19.

How Do You Use Force-Field Analysis to Make Decisions?

Developed by social psychologist, Kurt Lewin, force-field analysis examines the forces for and against some action, that is, forces for (pros) and forces against (cons) a decision (see Figure 3.2). Driving forces promote change, while restraining forces support the status quo (no change). In a force-field analysis, the decision or change being considered is listed in the middle, and the forces for and against the decision are listed in columns on either side of the choice. Each force is then assigned a number.

There are a number decision-making tools that function in similar ways to decision matrices, force-field analysis, and expert systems. These

Table 3.4
Expert system for selecting the most appropriate statistical text

Stats.expsys

```
Dec 1: “Univariate statistics.”
Dec 2: “Bivariate statistics.”
Dec 3: “Percentages, Proportions, Ratios.”
Dec 4: “One-sample Chi-Square.”
Dec 5: “Central Tendency: Arithmetic mean, Median, Mode. Dispersion: Range,
   Standard deviation, Variance.”
Dec 6: “Z-test.”
Dec 7: “T-test of sample and population mean.”
Dec 8: “Regression analysis.”
Dec 9: “Calculate correlation coefficient.”
Dec 10: “Calculate coefficient of determination.”
Dec 11: “Set table of means.”
Dec 12: “Analysis of variance.”
Dec 13: “Calculate correlation ratio.”
Dec 14: “T-test for difference between two sample means.”
Dec 15: “Set table of percentages or proportions.”
Dec 16: “Chi-Square for contingency.”
Dec 17: “Calculate Phi coefficient, Cramer v square coefficient.”
Question 1: “How many variables does this case deal with?”
   Answers 1 “Only one”
      2 “Two”
Question 2: “What is the measurement type of this variable?”
   Answers 1 “Nominal scale.”
      2 “Interval scale.”
Question 3: “What is the purpose of this univariate statistical case?”
   Answers 1 “To identify descriptive tools”
      2 “To test statistical significance of difference between sample and population.”
Question 4: “If standard deviation of population is know?”
   Answers 1 “Yes”
      2 “No.”
Question 5: “What are the measurement type of these two variables?”
   Answers 1 “Interval-interval scale.”
      2 “Nominal-interval scale.”
      3 “Nominal(2 categories)-interval scale.”
      4 “Nominal-nominal scale.”
Question 6: “What is the purpose of this bivariate statistical case?”
   Answers 1 “To describe relationship.”
      2 “To test statistical significance.”
      3 “To measure degree of association.”
Rule 1 :IF Q1A1 THEN Decision 1.
Rule 2 :IF Q1A2 THEN Decision 2.
Rule 3 :IF Q1A1 and Q2A1 and Q3A1 THEN Decision 3.
Rule 4 :IF Q1A1 and Q2A1 and Q3A2 THEN Decision 4.
```

Rule 5 :IF Q1A1 and Q2A2 and Q3A1 THEN Decision 5.
Rule 6 :IF Q1A1 and Q2A2 and Q4A1 THEN Decision 6.
Rule 7 :IF Q1A1 and Q2A2 and Q4A2 THEN Decision 7.
Rule 8 :IF Q1A2 and Q5A1 and Q6A1 THEN Decision 8.
Rule 9 :IF Q1A2 and Q5A1 and Q6A2 THEN Decision 9.
Rule 10 :IF Q1A2 and Q5A1 and Q6A3 THEN Decision 10.
Rule 11 :IF Q1A2 and (Q5A2 or Q5A3) and Q6A1 THEN Decision 11.
Rule 12 :IF Q1A2 and Q5A2 and Q6A2 THEN Decision 12.
Rule 13 :IF Q1A2 and Q5A2 and Q6A3 THEN Decision 13.
Rule 14 :IF Q1A2 and Q5A3 and Q6A2 THEN Decision 14.
Rule 15 :IF Q1A2 and Q5A4 and Q6A1 THEN Decision 15.
Rule 16 :IF Q1A2 and Q5A4 and Q6A2 THEN Decision 16.
Rule 17 :IF Q1A2 and Q5A4 and Q6A3 THEN Decision 17.

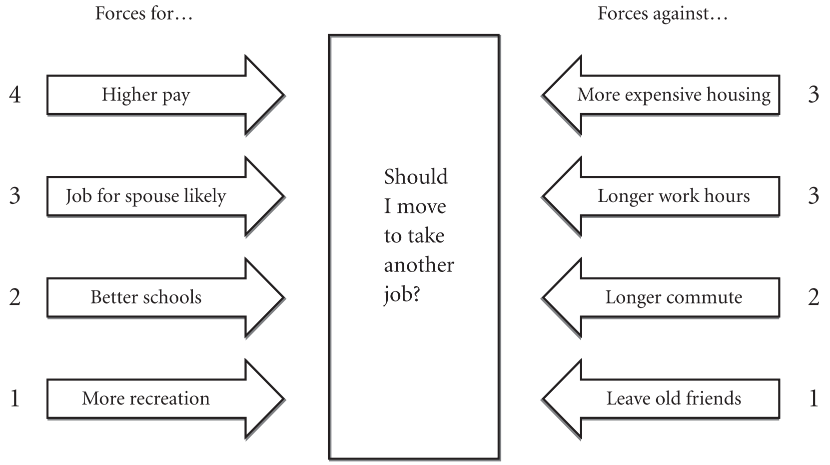


Figure 3.2 Force field analysis of decision.

include Pareto analysis, cost–benefit analysis, decision trees, and paired comparison analysis. All of these tools are intended to objectify the decision process as much as possible. Although I will later show that experienced decision makers seldom employ such objective strategies, these strategies are useful for scaffolding novices during the initial stages of learning. For experienced and expert practitioners, such strategies probably impede decision making more that they help.

DO PEOPLE REALLY MAKE RATIONAL CHOICES?

According to numerous instructional models for teaching decision making, such as Mann, Harmoni, and Power (1991), rational decision makers should systematically search for relevant information in an unbiased manner and then carefully weigh the utility of each alternative before making a choice. However, decision makers often fail to follow the prescriptions of these normative models (Hogart, 2005; Kahneman, Slovic, & Tversky, 1982). There are many reasons why humans do not make decisions rationally in order to maximize utility or value. First, rational-choice methods of decision making are based on the concept of unbounded rationality, which does not describe how real people think; they do not always seek to maximize their expected utility (Gigerenzer & Todd, 1999). People make decisions that satisfice, rather than optimize (Simon, 1957).

Second, the gambling conception of decision making is based on normative theory that implies that simple monetary structure provides a useful description of all everyday decisions and that the goal of all decisions is too maximize expected value (Rettinger & Hastie, 2001). That is, people make decisions based on values and probabilities inherent in situations without respect to domain. However, when making predictions under uncertainty, people do not calculate chance according to statistical theory (Kahneman & Tversky, 1982). Rather, they rely on a limited number of heuristics, which often lead to errors in reasoning, such as judgmental biases, representational faults, and coping defects (Jungermann, 2000). Cohen (1993) showed that gambling results in decision biases, such as lack of available heuristics, making a first best guess followed by adjustments, overconfidence in decisions, assigning higher values to rare events, failure to revise decision in light of new evidence, and assigning more value to favorable outcomes and less value to unfavorable outcomes. Almost all of the empirical research on gambling and expected value were examined in terms of laboratory tasks, where decisions were made among a relatively small number of options. Everyday decisions are seldom so constrained. In fact, depending on the importance of the decision and the kind of decision that must be made, people may employ a variety of strategies for making those decisions (Beach & Mitchell, 1978).

Third, humans are subject to numerous biases in reasoning, including making holistic decisions based on a single dimension (e.g., single-issue voters) and a concomitant unwillingness to make trade-offs; myside bias, which is a consistent preference for personal beliefs and an unwillingness to consider counterarguments should remain open to counterevidence (Baron & Brown, 1991). Additional biases include the sunk-cost effect, where decision makers persist with plans that have big investment after they should give up, and neglecting uncertain outcomes (e.g., Why give to charity when money may be wasted?). All of these biases indicate that humans are less rational than normative theories of decision making predict. Shanteau, Grier, Johnson, and Berner (1991) found that when making decisions, nurses made ineffective use of information (e.g., seeking too much information where too much was deemed essential), inaccuracies of probability judgments (e.g., undermedication to reduce risk), and inability to evaluate alternatives and choose appropriate actions.

Fourth, another reason that normative theories do not work is known as Fredkin's paradox (Minsky, 1986). According to this paradox, as options become more closely matched in utility, the decision becomes more difficult to make because the consequences become less significant. When options are close to identical in terms of weighted values, the decision is hardest.

In summary, decision theory is not cognitively compatible with the way that experienced decision makers work (Cohen & Freeman, 1996). By demanding a complete model up front, decision theory does not account for the dynamic evolution of decision problems. Nor does it account for qualitative differences in the ways uncertainty is handled. Statistical theories of decision making represent decisions as domain- or knowledge-neutral. Glasspool and Fox (2005) conclude that normative theories of decision making have little to say about how people actually make decisions or reason under uncertainty. Most decisions are made in the absence of statistics. They argue that deciding based on statistical analysis necessarily abstracts and decontextualizes the decision, but decision making is not knowledge neutral. "Although normative theorists prescribe invariant and regular decision-making processes, human decision makers rarely, if ever, exhibit them" (Rettinger & Hastie, 2001, pp. 338–339).

HOW DO PEOPLE REALLY MAKE DECISIONS?

In this section, I describe various descriptive models of decision making. These models describe how people make decisions in naturalistic settings rather than describe how people should make decisions. Unlike rational approaches to decision making that conceive of decision-making processes as statistical comparisons of knowledge-neutral options, these descriptive approaches assume that decision making is a knowledge-based activity where people contrast decision options based on the meaning and motivations behind each option. Decisions about surgical options are not made the same way as deciding which horse to bet on at the track. That is, decisions are not made without considering what each option means as well as the implications of each option. When human decision making is observed and analyzed, a different picture of decision making emerges. Issues in descriptive decisions are discussed next.

The most prominent descriptive theory of decision making is known as naturalistic decision making (Klein, 1999; Zsambok & Klein, 1997), which describes complex, high stakes, poorly defined, critical decision-making processes under stress. Decision making does not involve comparing two or more options. For example, fire commanders do not compare options using any rational process; they come up with a course of action to start and run mental simulations to test various options. These complex tasks, I believe, go well beyond our normal conceptions of decision making. They represent what I referred to in Chapter 1 as strategic performance problems, so I will describe naturalistic decision making more completely in Chapter 5.

WHAT IS THE ROLE OF CONTENT AND CONTEXT IN DECISION MAKING?

Contemporary research on decision-making, known generally as explanation-based decision making, provides compelling evidence that people construct different kinds of explanations about decision options in order to make decisions. Those explanations are usually constructed in the form of a story that has a causal structure to guide decision making. The assumptions of these descriptive, explanation-based theories are substantively different from the normative theories described earlier in the chapter.

Explanation-based decision making is premised on the assumption that the content of any decision exerts direct influence on choice of decision strategy (Rettinger & Hastie, 2001). Problem solving is, to a large degree, domain-specific. These alternative patterns of decisions in different domains are related to differences in subjective evaluation of each outcome. Why? Because different domains induce different decision schemata and choice strategies. Those decision strategies include numerical calculations, story construction, regret focus, morality focus, choose the favorite, avoid the worst, and other emotional reactions. What causes change in decision strategies? Rettinger and Hastie argue that the personal importance of the decision leads to more elaborate narrative processing. Decision makers naturally elaborate information with personal background knowledge, especially when outcomes are concrete (e.g., measured in terms of lives).

WHAT IS THE ROLE OF STORIES IN DECISION MAKING?

So, decision makers often construct explanations of alternative outcomes in order to evaluate them. The decision options with the most compelling explanation are usually the ones that are selected. What makes an explanation compelling? It seems that narrative provides the most compelling explanation. As indicated in Chapter 12, narrative is the most natural form of communication and sense making in humans. When faced with decisions to convict or acquit, jurors face a massive database of evidence presented at trial in a scrambled sequence by different witnesses. In order to make sense of that data, jurors spontaneously construct stories based on the trial evidence (Pennington & Hastie, 1986). They also found that jurors were twice as likely to find a defendant guilty when the prosecution's evidence was presented in story form and the defense's evidence was not. All evidence was rated higher when presented in story form. These research results imply that story construction is an essential part of evidence comprehension that helps to determine a decision, while the coherence of story structure and strength of alternative stories predicted jurors' confidence in their decisions. However, it is not just the coherence of story that affects decisions but also the strength of one story when compared with another. Pennington and Hastie (1986, 1988) found that jurors impose a narrative story on trial evidence, including evidence evaluation through story construction, alternative representations of decisions (establishing verdict categories), and story classification (selecting verdict that best fits story). Reconstruction is an historical story. Episode schemas contain initiating events, goals, actions, consequences, and accompanying states in a causal configuration.

What makes stories so compelling? Stories are the "means [by] which human beings give meaning to their experience of temporality and personal actions" (Polkinghorne, 1988, p. 11). Narrative discourse is comprehended through basic conceptual schemas that describe most human actions (known as episodic schemas). So the jurors' stories represent the complex and convoluted evidence presented at trial as a hierarchy of embedded episodes. Pennington and Hastie (1992) interviewed students after watching a three-hour video of trial evidence and found that these students constructed stories of the evidence with causal-event-chain and episode structures, and that students' stories varied with verdict choice both in content and structure. When evidence was organized in story order, people recalled more of the evidence. Once again, story structure was a mediator of decisions and of impact of credibility of evidence.

When jurors organize and represent trial evidence in the form of stories, they embellish those stories with their own personal world knowledge about similar events, which they then try to match to verdict options provided by judge (Pennington & Hastie, 1993). Those episodic schemas contain a variety of constructs, including initiating events, goals, actions, consequences, and accompanying states in a causal configuration. These episodic schemas are similar to scripts that were defined by Schank and Abelson (1977).

The role of story construction in decision making was verified in terms of investment decisions (Mulligan & Hastie, 2005). When information about investment options was presented in narrative form, decision makers constructed coherent mental models that influenced their predictions of stock prices. That outcome information had a large impact when it was presented in story order. Clearly, presentation order influences the mental representation of information used to make forecasts and to influence judgments. So, rather than statistically comparing decision options without regard to their content or means of representation, descriptive research on decision making has shown that evaluating decision options is more a process of constructing stories about the outcomes of each option and matching those outcomes to goals. These findings fundamentally change the assumptions that normative theories make about decision processes.

In addition to the empirical evidence supporting descriptive theories of decision making, there is recent neurological evidence in support of explanation-based decisions. Research by Li, Mayhew, and Kourtzi (2009) shows that past experience is very helpful when making complex decisions based on uncertain or confusing information. They show that learning from experience actually changes the circuitry in our brains so that we can quickly categorize what we are seeing and make a decision or carry out appropriate actions, so knowledge of decisions is important to the process. Motivations are also critical to decision making. Lehrer (2009) provides compelling evidence that emotions are a critical part of the decision-making process. When cut off from feelings, decision making becomes impossible, so the limbic system is inextricably involved in decision making.

WHAT IS THE ROLE OF CAUSALITY IN DECISION MAKING?

One reason for the failure of expected utility models is that they ignore causal effects of different options. They fail to appreciate that a decision is an intervention (Sloman, 2005), so choosing an option can be represented only with the predictive logic of intervention. Do not forget that a decision will be made as soon as there is a commitment to act, so that decision making is an intentional behavior (Yates & Tschirhart, 2006). The results of that decision will result in different effects. That is, each decision option necessarily manifests different sets of causal relationships. Every decision that we make has causal consequences.

Decision makers begin by constructing an explanatory representation in story form that contains causal accounts (see Chapter 17 for an explication of causality) of the evidence in legal decisions (Pennington & Hastie, 1988, 1993). In order to interpret events, people organize those events around causal schemas (Tverky & Kahneman, 1980). Those causal schemas are acquired through experience. Why are story schemas organized causally? Because causal inferences are used to interpret events. That is, causal understanding of events enables people to make predictions about the effects of causal conditions on outcomes and to infer the causal conditions that resulted in some outcome (Jonassen & Ionas, 2008). Causal schemas evolve from causes to consequences, so it is easier to reason from causes to consequences (prediction) than consequences to causes (diagnosis) (Tversky & Kahneman, 1982). Subjects in their study judged causal (prediction) conditional probabilities to be higher than diagnostic ones, so predictions are made with greater confidence than diagnosis. When data have both predictive and diagnostic evidence, prediction data is given greater weight. Causality affects decisions. Causally relevant facts have more influence than causally irrelevant.

While episodic schemas using in decision making are causally organized, the structure of the model is domain-dependent. In medicine, diagnosis constitutes a model of the patient. That is, the model is a causal story of what happened to bring the patient in (forming a picture of the patient). Explanation and diagnostic disease category have well-specified causal structure. Causal structures are domain-specific. For example, a physician's causal model of a patient's physiological condition is different from an engineer's mental model of an electrical circuit or cognitive model of a power plant. Domain specificity has huge implications for the role of domain knowledge as part of problem-solving teaching and assessment.

How do people apply causal reasoning to decision making? Decisions are made when the causal model of evidence is matched to an alternative in the choice set. According to Pennington and Hastie (1993), decision makers begin the decision process by constructing a causal model to explain the available facts. As illustrated in Figure 3.3, people

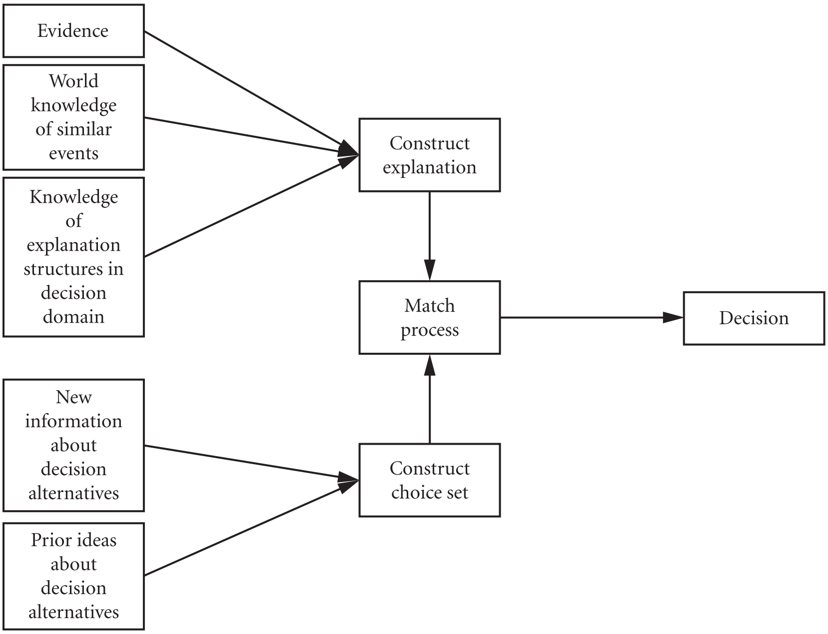


Figure 3.3 Matching causal models of evidence to solution options (Pennington & Hastie, 1993).

construct causal explanations that consist of case evidence that has been causally reorganized, world knowledge about similar events, and knowledge of causal structures. Next, they create potential solutions. Finally, they match each solution alternative to the evidence representations and select the solution that most closely matches their causal model. Their confidence in their decision is based on the coherence (completeness, plausibility, consistency) between their model and the solution. The decision-making process results in mental representation of evidence, incorporating inferred events and causal connections between events. There exists a prevalent danger in this kind of thinking: implying causality between events when none exists (the common problem of inferring causation from correlational data) (Hastie & Dawes, 2001).

Policy scholars have developed methodologies for constructing causal maps to aid in decision making. Axelrod exemplified a graph theoretical method for representing complex foreign-policy decisions, which are "designed to capture the structure of the causal assertions . . . with respect to a particular policy domain, and generate the consequences that follow from this structure" (1976, p. 58). These maps can be derived from documents or questionnaires sent to knowledgeable judges. The maps include alternative proposals and the causal relationships linking them, all conveyed in node-link maps. The nodes in these causal maps consist of concepts that represent variables, and relationships are represented as causal links between the nodes, each conveying increases and decreases between the variables. For example, during the first decade of the twenty-first century, America was embroiled in a war in Iraq. During that decade, the debate about whether to remain in or withdraw from Iraq raged on. Figure 3.4 illustrates the beginnings of a causal map that conveys some of the many possible causal relationships associated with the decision. The pluses and minuses represent positive and negative effects. While scholars will argue about the validity of any of the variables and relationships conveyed in the map, what is important is that the map provides a focus for conducting those discussions. Causal maps represent a form of scenario generation that can assist in making complex, multi-faceted decisions. Similar maps can be constructed using influence diagrams or causal diagrams (see Chapters 17 and 19).

How Can People Represent Their Causal Models?

If decision makers construct causal explanation of information to compare to different options, learners need some method for learning how to construct those explanations. Although little empirical research is available in the learning literature, I believe that scenario-based explanations provide a powerful tool. Scenarios are stories that are constructed to predict future events in times of uncertainty. They are described further in Chapter 6. The stories describe possible future

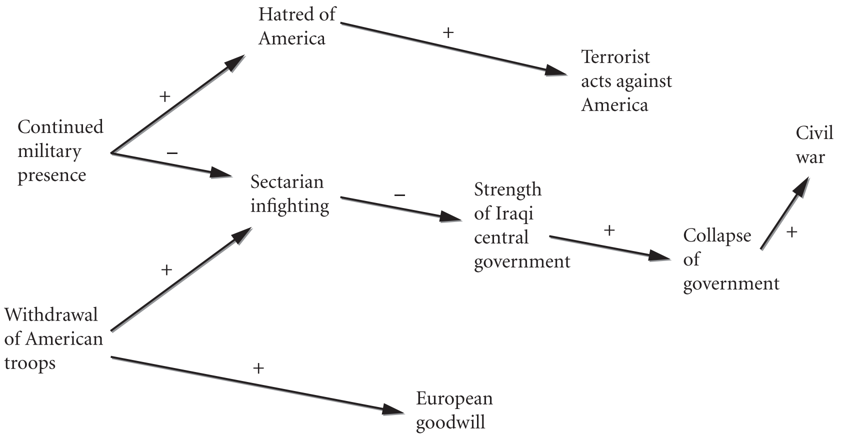


Figure 3.4 Causal map of policy decision.

outcomes based on complex interactions of cause–effect relationships among the situational, that is, an explication of chain of actions and events and their causal relationships (Kahn, 1965). Construction of scenarios is an important method for assessing long-range economic, political, and societal developments. For example, scenarios have been used to inform important military and political decisions such as:

- Should President Kennedy blockade Cuba in 1962?
- Should the first atomic bomb be detonated over Hiroshima?

Would that a longer-term scenario have been built to predict the effects of the US invasion of Iraq to topple Saddam Hussein.

Political and economic decisions also call for the construction of scenarios, such as:

- What are the economic, health, and social effects of raising the tax on cigarettes by $1 per pack?
- Should we grant marriage benefits to same-sex partners?
- How will constant connectivity through mobile devices affect identity formation in the next generation?
- Should water be diverted from the upper Colorado River basin to support population growth in Denver?

Scenarios necessarily have a causal story structure that predicts the outcomes of various interventions. They tell a story about what we believe will happen. The events in the story are based on causal relationships. The structure of any scenario can be conveyed in the form of a causal map (see previous section). For example, historians argue about the reasoning that Truman considered when deciding to use the first atomic weapon. He predicted, some believe, that it would reduce loss of lives overall, demoralize the Japanese, and strengthen America's hand after the war. Truman no doubt constructed such a scenario while making that horrific decision.

According to Kahn (1965), a scenario is

- **hypothetical**, representing a possible future (although historians also construct scenarios in retrospect to test counterfactuals);
- **selective**, representing one possible state of complex, interdependent, and dynamic affairs;
- **bounded**, consisting of a number of states, events, actions, and consequences that may occur in the future;
- **connected** by causally related elements and events; and
- **assessable**, providing a judgment based on probability.

Most scenarios are exploratory or anticipatory where the scenario constructor starts with some states and anticipates future consequences (making predictions), although some are normative, where scenarios describe futures as they should be. Scenarios present a chain of causally related events resulting from the implementation of some option and leading to some outcome (Tversky & Kahneman, 1980). The network of causally related events in the scenario can take on various states depending on which actions are taken. Scenario generation is a kind of mental simulation of future events. The pictures that we draw while exploring the future are scenarios (Thuring & Jungermann, 1986).

In order to construct a scenario, the following steps should be undertaken:

1. Identify the most important external factors and their level of uncertainty.
2. Using the most important yet uncertain factors, construct multiple stories of the events or outcomes that may results causally from those factors.
3. Identify possible interfering events and probabilities and impacts.
4. Determine how those different stories affect strategic planning and decision making of the organization.

The ultimate goal of forecasting through scenario construction is to guide action, that is, decision making (Einhorn & Hogarth, 1982). For example, economic forecasters predict recession for the next year and the government lowers the tax rate to stimulate the economy. Sometimes, scenarios become a self-fulfilling prophesy where actions are taken to confirm the prediction. For example, a rumor that banks may be in trouble causes a run on bank deposits, which causes the banks to be in trouble.

For purposes of designing problem-solving learning environments, scenario construction can be used to support or assess the ability to make meaningful decisions. For a variety of decision options, learners may be required to construct plausible scenarios about the outcomes of each option. The scenarios that learners construct can also be effectively used to assess student understanding of the relationships that describe any system. Instructors should assess each scenario for plausibility and coherence. It should be readily obvious to any instructor how well students understand systems by the predictions that they make.

WHAT IS THE ROLE OF ARGUMENTATION IN DECISION MAKING?

Another conception of decision making is argumentation (see Chapter 20 for a more elaborate discussion about argumentation). That is, when people make choices when they lack information about probabilities and outcomes, they tend to generate arguments that allow them to resolve the conflict (Hogarth & Kunreuther, 1995).

One of the more prominent models of explanation-based decision making that uses argumentation is the Domino model (Glasspool & Fox, 2005). Domino, which was tested with medical decisions, provides a framework for understanding the context in which decisions are made, including the motivations for making the decision and the fundamental form of reasoning. Decision makers use a form of argumentation rather than calculating expected values. Constructing arguments requires knowledge of the options, unlike expected value methods. In order to make decisions, people generate arguments for and against each option on the basis of their knowledge of the world and combine those arguments to reach a decision. Making a decision then is a process of supporting or rejecting alternative claims (decisions). According to their model (see Figure 3.5), Glasspool and Fox (2005) describe the argument-based decision-making process as a series of mental activities. First, the decision maker identifies candidate explanations (claims). Then people make any number of arguments for and against alternative claims

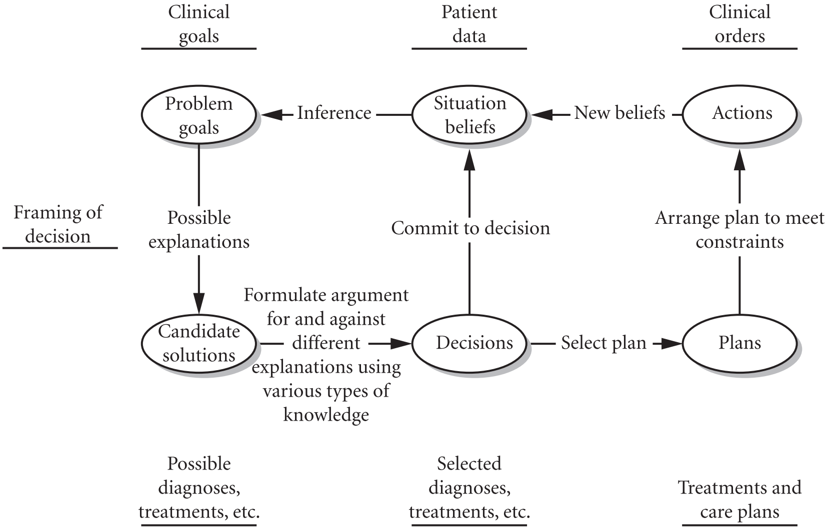


Figure 3.5 Domino model of decision making.

(options), drawing on different theories. Each theory is supported by different forms of evidence. In order to make decisions, we assess arguments for and against each claim. The Domino model provides a way to understand the cognitive processes of the decision maker.

WHAT HAVE WE LEARNED ABOUT DECISION MAKING?

Decision making involves the selection of one or more beneficial or satisfying options from a larger set of options. Decision makers may be selecting choices from a list of options, accepting or rejecting an option, or evaluating the worth of options. Traditional, laboratory-based research on decision making conceived of selecting the best options as a process of calculating risk or opportunities in order to maximize the expected value from the decision. Rational choice methods identify criteria, evaluate each decision based on those criteria, weight the options, and select the option that maximizes expected value. Although widely used in management, these normative models fail to consider the role of domain or contextual knowledge in decision making.

More contemporary research on decision making regards decision making as an explanation-based process. That is, the decision maker must be able to make sense of the evidence that is collected to aid the selection process. In order to select options, people must construct coherent explanations about the outcomes of each option. The most common method for doing that is story construction. That is, as people collect evidence to support a decision, they construct stories about the outcomes of each decision. Those stories tend to have a strong causal structure. For example, the Federal Reserve decreases interest rates to banks to reduce the cost of borrowing, which induces more borrowing, which puts more money into circulation, which increases the money in use, which increases the money in circulation, which results in inflation. This is the kind of scenario construction that economists regularly construct. Finally, decision making may be conceived as an argument among alternative claims. By constructing arguments, anticipating counterarguments from other options, and rebutting those options, decision makers make a selection among options.

Decision making is a psychological process and, like most psychological processes, is performed inconsistently. The number of options being considered, the potential loss resulting from a decision, the level of uncertainty about optional outcomes, and the number of potential tradeoffs all make decision making very difficult (Hastie & Dawes, 2001), especially the everyday and professional decisions that cannot be objectively described as probabilities and numerical values.

WHAT ARE THE COMPONENTS OF A DECISION-MAKING LEARNING ENVIRONMENT?

Although there exists no research literature comparing alternative methods for learning how to make decisions, my analysis of the process suggests different methods (see Figure 3.6). Although rational-choice approaches appear not to be the primary mechanism by which people make decisions, they probably have some instructional utility, especially for novices. There are advantages to a rational-choice strategy (Klein, 1998):

- It should result in reliable decisions.
- It helps novices determine what they do not know.
- It is rigorous (does not leave anything out).
- It is a general strategy that is applicable in different situations.

Figure 3.6 illustrates two options on the right side of the figure. Help learners to construct a force field or SWOT analysis for

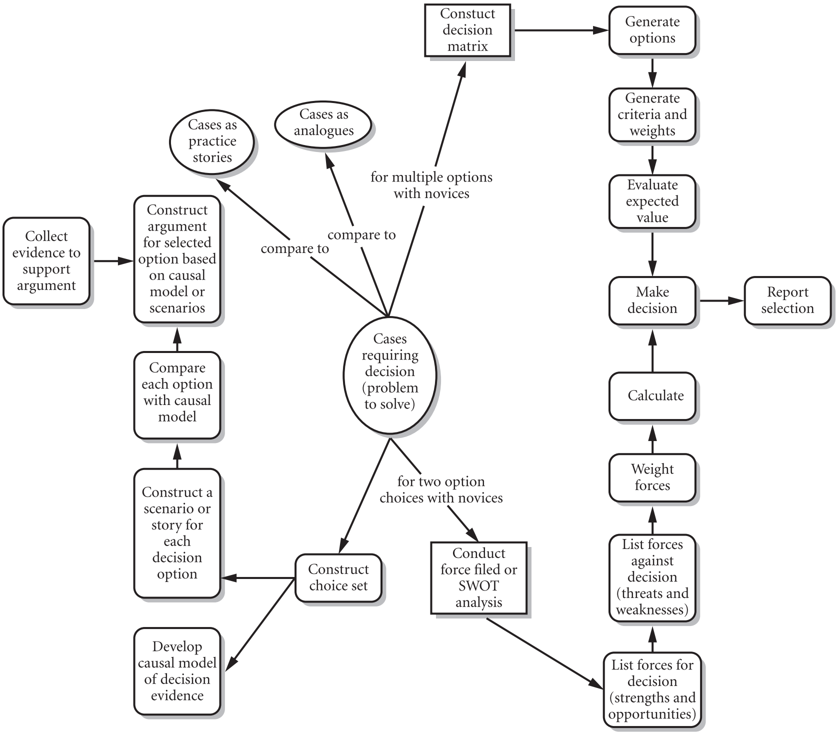


Figure 3.6 Optional instructional approaches for decision making.

acceptance–rejection, two-option decisions. For choices, evaluations, or constructions with multiple options, help students to construct a decision matrix. The weighted criteria make the choice fairly simple: the option with the greatest expected value. However, you may want to have novices complete activities illustrated on the left side of Figure 3.6 after completing the more rational analysis of choices.

For more experienced learners or novices who have previously completed a rational analysis of choices, help them to construct a set of options. With the set of options, they can either construct a causal model of the decision and compare the outcome of each decision with that model or help students to construct a scenario for each option to identify the potential outcomes. For the novice, these activities will provide a reality check on the rational analysis and for the advanced student an opportunity to display a deeper level of understand about the decision.

For all students, provide analogous decisions to compare to the one currently being made or provide cases describing the experiences of other decision makers who have solved similar decision-making problems in the past. These will provide significant insights to the decision maker.

HOW DO WE REPRESENT DECISION PROBLEMS TO SOLVE?

Decision-making problems, like all kinds of problems, are the central focus of instruction. Like most other problems, we represent decision-making problems as stories because they are better understood, better remembered, and more empathic than didactic representations of problems. Figure 3.7 illustrates a decision-making problem facing hotel-and-restaurant-management students. Clicking on the discussion button shows the transcript of a discussion among the principals seated at the table.

How Can Case Studies Be Used?

Because decisions such as this can become very complex, it would be useful for students to analyze case studies of other expansion projects that have been considered by other hotel chains. Those case studies could elucidate the factors that decision makers need to consider.

How Can Alternative Perspectives Be Used?

In such a complex decision, perspectives are diverse and often contradictory. First, there are the perspectives represented by the principals in the discussion. Unpacking those positions will probably yield a host

HOTEL MANAGEMENT STRATEGIC PLANNING LEARNING ENVIRONMENT

The Case

Evan is the Chief Executive Officer of a large hotel chain. One of the company's strategic initiatives calls for a 2-5 year plan for expansion. This strategy is primarily based on the fact that the industry is generally a growth industry, and also on the fact that Evan's company has seen several years of increased revenue growth. The company's general officers and board members believe that, in order to stay competitive, a growth strategy is the best approach. Evan is now tasked with defining exactly what that strategy will be.

Personally, Evan believes that one of their first projects should be to add up to 1,000 rooms to their hotel/casino in Las Vegas. He has asked one of his interns, Irene, to write a report justifying the expansion. He tells Irene to work with key members of his staff; Oliver, the Chief Operating Officer, Felicia, the Chief Financial Officer, their Human Resources Officer, Harriet, and their Marketing Officer, Mark. They agree to work as a team to evaluate Evan's idea and develop a recommendation.

Figure 3.7 Representation of a complex decision-making problem.

of themes based on economic, recreational, and personality factors (see Chapter 13).

How Can Causal Reasoning Be Used?

The causal factors involved in such a decision are complex and interactive. In this environment, we provide a SWOT analysis tool where students can examine the direct and indirect effects of each of the decision factors. These factors are often interactive, and so a SWOT analysis may not be sophisticated enough. Building a systems model of the decision situation (see Chapter 19) would probably be a stronger way of testing causal relationships.

How Can Argumentation Be Used?

If treated as a yes-no decision, argumentation for or against a decision may be structured using a force-field analysis (described before). However, it is likely that the best decision may involve multiple options and considerations, so a more complex form of argumentation representing rebuttals to each option, may be more appropriate. Another implicit form of argumentation is scenario construction, where proponents and opponents construct scenarios that describe the potential results of their preferred decision. Regardless of method used, argumentation is central to most decision-making problems.

4

TROUBLESHOOTING AND DIAGNOSIS PROBLEMS

WHAT IS TROUBLESHOOTING?

Troubleshooting is among the most common types of problem solving. In fact, when people think about problem solving, they associate it strongly with troubleshooting and diagnosis. Whether troubleshooting a faulty modem, a multiplexed refrigeration system in a modern supermarket, a patient with an unknown malady, a car that will not start, or communication problems on a committee, troubleshooting attempts to isolate fault states in a system and repair or replace the faulty components in order to reinstate the system to normal functioning. Troubleshooting is normally associated with the repair of physical, mechanical, or electronic systems. However, organizational ombudsmen, such as employee-relations managers, customer-relation specialists, consumer advocates, public-relations specialists, and human-resource directors are also troubleshooters (Ziegenfuss, 1988). These people are responsible for handling complaints that represent fault states in the attitudes of customers that must be repaired in customer-relations systems. Individuals in their everyday lives engage in personal troubleshooting associated with self-change, especially when related to addictive behaviors (Prochaska, DiClemente, & Norcross, 1992). Psychotherapists are also troubleshooters, attempting to isolate the cause of mental problems.

Troubleshooting/diagnosis problems are moderately ill structured. There is usually a finite problem or set of problems that are causing difficulties. Troubleshooting problems:

- appear ill defined because the troubleshooter must determine what information is needed for problem diagnosis (which data about the electrical and fuel systems are needed in troubleshooting a car that will not start);
- require deep-level understanding of the system being troubleshot (how do electrical, fuel, and mechanical systems interact);
- usually possess a single fault state, although multiple faults may occur simultaneously (e.g., faulty battery, clogged injector);
- have known solutions with easily interpreted success criteria (part replacement leads to system restart);
- rely most efficiently on experience-based rules for diagnosing most of the cases, making it more difficult for novices to learn (mechanics rely first on experiences for diagnosis);
- require learners to make judgments about the nature of the problem; and
- vary significantly in terms of system complexity and dynamicity (age, manufacturer, engine size, reliance on computer controls in the automobile).

Troubleshooting is predominately a cognitive task that includes the search for likely causes of faults through a potentially enormous problem space of possible causes (Schaafstal, Schraagen, & van Berlo, 2000). How many potential faults can there be in an automobile or the human body? In addition, to fault detection or fault diagnosis, troubleshooting usually involves the repair or replacement of the faulty device. Replacing an ignition coil or repairing a lesion in the lining of the intestine will correct the problem. The emphasis in troubleshooting, though, is on fault diagnosis, which involves a search for the components of the system that are producing substandard outputs (cause of discrepancy). Troubleshooters then search for actions that will efficiently eliminate the discrepancy (Axton, Doverspike, Park, & Barrett, 1997). Medical diagnosis and treatment require more than troubleshooting. Although the diagnosis process is primarily troubleshooting, medical problem solving exemplifies diagnosis-solution problems, because selecting the best solutions becomes more complex and ill structured.

WHAT KNOWLEDGE AND SKILLS ARE REQUIRED TO TROUBLESHOOT?

Troubleshooting is usually taught as a linear series of decisions that direct the fault isolation. Flowcharts and decision tables are frequently used to lead the novice troubleshooter through a series of decisions or actions that will hopefully isolate the fault. This approach often works with simple troubleshooting problems, but it is inadequate for training competent or proficient troubleshooters. This section describes the skills that troubleshooters need develop in order to move from novice, through advanced beginner, toward competent performers (Dreyfus & Dreyfus, 1986). Expertise results from years of reflective practice and is beyond the scope of this chapter or book.

In the transition from novice to competent performer, learners construct increasingly richer conceptual (mental) models of the systems they troubleshoot. Those models contain multiple representations of the system. As troubleshooters obtain more experience, they rely less on their conceptual models and more on the event schemas they construct from their experiences. Boshuizen and Schmidt (1992) showed how with experience in medicine, domain knowledge becomes encapsulated in clinical experiences. Schmidt and Boshuizen (1993) showed that acquiring expertise in medicine begins with rich causal networks of biological and pathophysiological processes. Extensive exposure to patient problems embeds their knowledge into higher-level narrative structures referred to as "illness scripts." Illness scripts for automobile mechanics correspond to specific equipment or subsystem malfunctions on particular brands and vintages of cars. Mechanics often describe tendencies for specific parts to fail in cars with different ages or manufacturers. That knowledge is represented as patterns of symptoms that are normally associated with specific fault states in specific cars. Experienced troubleshooters recognize the pattern of symptoms associated with different fault states, which enables the troubleshooter to rapidly activate solution scripts (Besnard & Bastien-Toniazzo, 1999; Gaba, 1991). Those event schemas (e.g., illness scripts) that are used to trigger solutions consist of well-integrated domain knowledge, contextual information, and episodic memories. What makes these event schemas so resistant to decay is the rich contextual information that surrounds the various events.

What kinds of knowledge do novices need to construct during the transition from novice to competent performer? Learning to troubleshoot begins with the construction of a conceptual model for the system that includes domain knowledge, system or device knowledge, visual-spatial knowledge of the system or device, procedural knowledge of how to perform tests and information-gathering activities, and strategic knowledge that guides search activities. I describe each of these knowledge states next. As the troubleshooter gains experience, these knowledge types become embedded within troubleshooters' memories of their experiences. They come to rely more on their historical knowledge of problems they have troubleshot than their conceptual models. Rather than working through a faulty system conceptually, experienced troubleshooters match new problems with their own event schemas resulting from their experiences and apply the solutions from those experiences to solve the current problem. Learning to troubleshoot involves a gradual shift from conceptual knowledge of systems and context-independent knowledge of strategies to personal, context-dependent memories of similar problems.

WHAT KNOWLEDGE STATES SUPPORT TROUBLESHOOTING?

Rasmussen (1984a) argued that troubleshooters must understand the device or system they troubleshoot at different levels of abstraction:

- **purpose of the system** (production-flow models, system objectives);
- **abstract functional model of the system** (causal structure or information-flow topology);
- **generalized functions of the system** (standard functions and processes and control loops);
- **physical functions of the system** (electrical, mechanical, chemical processes of the components); and
- **physical forms in the system** (physical appearance and anatomy, material, and form).

Auto-mechanics and physicians must understand the engine or body being troubleshot in terms of the location of all of the components, the flow of fuel, air, water, and electricity through those components, the functions of those flow states and the reasons for changes in them. Without understanding the system being troubleshot on those levels, troubleshooters are unable to generate adequate fault hypotheses. The multiple representations of problems that expert troubleshooters possess allow them to generate more fault diagnosis and solution strategies (Ericsson & Smith, 1991). The following kinds of system knowledge are most generally accepted as essential for troubleshooting.

How Much Domain Knowledge Is Necessary?

Domain knowledge refers to the general theories and principles upon which the system or device was designed. For example, Ohm's law is a foundational principle used to describe the flow of electricity from the battery, through the starter, and to the spark plugs. Johnson, Flesher, and Chung (1995) argued that theoretical knowledge may not be as important as educators believe in training competent technical system troubleshooters. Their study found that there was no difference between high and low troubleshooting performers' theoretical knowledge of the system. Students' theoretical knowledge did not predict their competence in troubleshooting a technical system fault (Johnson, Flesher, Jehng, & Ferej, 1993). Morris and Rouse (1985) concluded that providing instruction about theoretical principles is not an effective way to train troubleshooters. Domain knowledge is a necessary condition for beginning troubleshooters, but it is not sufficient for learning to become a competent troubleshooter. Domain knowledge is important when troubleshooters transfer their skills to different systems (MacPherson, 1998), and domain knowledge is necessary for constructing deeper understanding of the system (Johnson et al., 1995), as reflected in system or device knowledge (described next).

What Kinds of System or Device Knowledge Are Necessary?

The primary differences between expert and novice troubleshooters are the amount and organization of device knowledge (W. Johnson, 1988). Conceptual knowledge of how systems works is fundamental to the understanding of any technical system (Chi, Feltovich, & Glaser, 1981; Johnson et al., 1995; Larkin, McDermott, Simon, & Simon, 1980). System or device knowledge is an understanding of "(1) the structure of the system, (2) the function of the components within the system, and (3) the behavior of those components as they interact with other components in the system" (Johnson & Satchwell, 1993, p. 80), and the flow control within the system (Zeitz & Spoehr, 1989). Again, automechanics understand how the components (air, fuel, and electricity) of an automotive system interact with and affect each other. Of course, the quality of the conceptual models required depends on the level of intervention expected. For example, an electronics technician who only replaces circuit modules only needs to understand the block diagram of the circuit. Skilled troubleshooters are better able to troubleshoot outside their specialty because they know how the components of any system work, what their functions are, and how they are related to the system as a whole (Lesgold & Lajoie, 1991). It is also important to point out that troubleshooters have a different kind of knowledge of a system than designers do. Designers know in great detail how the system is supposed to work but may not know much about failure modes and system component interactions during failures, and they may not know much about the cost–time tradeoffs for various tests and interventions.

System knowledge includes topographic and functional knowledge.

Topographic models of the system are spatial representations of the components of a system (Rasmussen, 1984b). Topographic knowledge of automobile systems would include representations of the location of each component within the engine or around the automobile. Fuel filters, for instance, can occupy a wide variety of locations within the engine compartment, depending on the manufacturer and model. Rasmussen showed that experts search for faulty components by means of topographic representations of the system being troubleshot (a diagram of the system). In another study, Johnson (1988) showed that experts reduced problem space size using a topographic search of the system in an efficient sequence. Topographic searches enable skilled troubleshooters to select hypotheses that bring them closer to the fault. Novices meanwhile generated hypotheses randomly within and outside the problem space. Topographic knowledge predicted troubleshooting performance (Rowe & Cooke, 1995; Rowe, Cooke, Hall, & Halgren, 1996).

Topographic knowledge is normally conveyed as diagrams depicting the structure of a system. Manufacturing troubleshooters, for example, must hold a mental image of the components of the system and their outputs in order to identify system malfunctions (Axton et al., 1997). More successful topographic models include not only an image or diagram of the physical characteristics of the system but also different information paths or routes through the system. So the search for faults often involves testing the system along these different information paths. Jonassen and Henning (1999) used a method described by Tversky, Franklin, Taylor, and Bryant (1994) where troubleshooters generate written protocols depicting a visual tour of the system being troubleshot along various routes. More successful troubleshooters provided more accurate topographic descriptions of the systems.

Functional knowledge, as opposed to topographic, is the comprehension of each individual component's function in a given system and the causal relationships between the components and their structure (Sembugamoorthy & Chandrasekaran, 1986). For example, functional knowledge of automobile systems includes understanding how spark timing and valve timing both interact to affect combustion. Skilled troubleshooters organize their topographic models based on functional descriptions of the device (Gitomer, 1988). Thagard (2000b) analyzed the process of diagnosing disease states and concluded that physicians' explanations of diseases use causal networks to depict the combination of inferences needed to reach a diagnosis. Jonassen, Mann, and Ambruso (1996) constructed a causal, diagnostic model used to diagnose a hematology disorder known as thrombocytopenia (see Figure 4.1). When

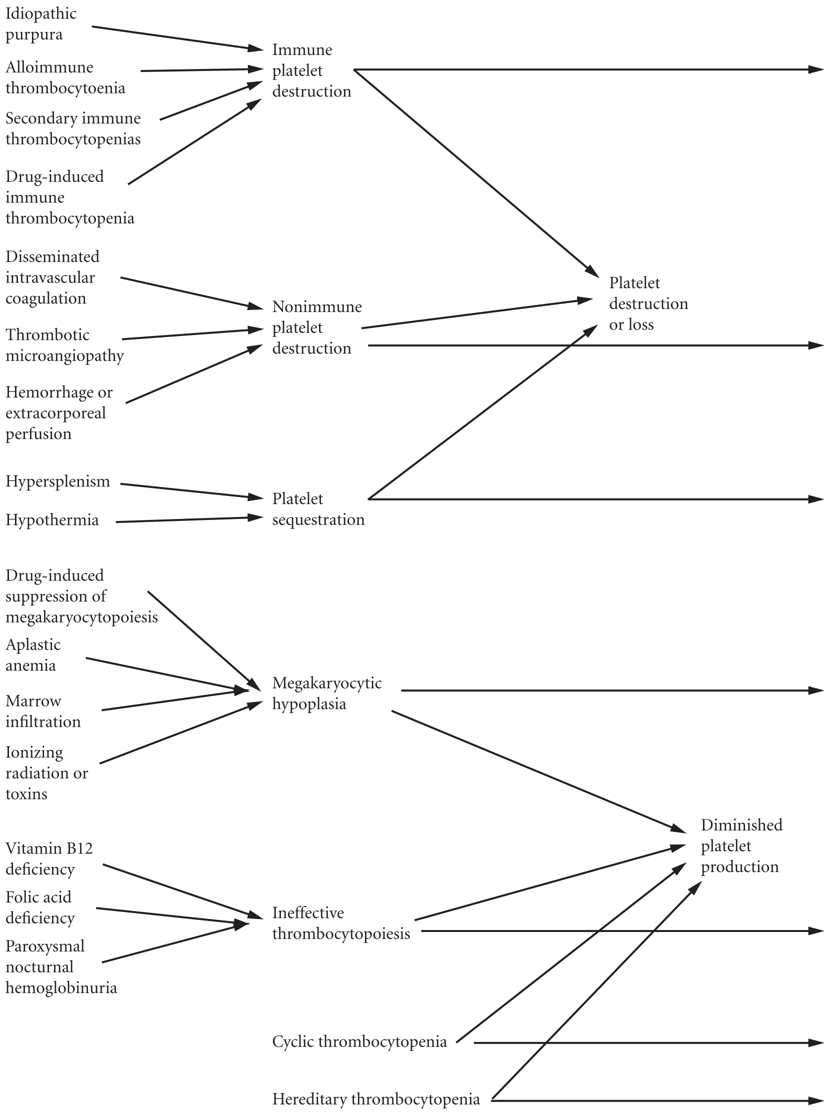


Figure 4.1 Causal (diagnostic) model of medical diagnosis.

debugging electronics systems, David (1983) found that skilled troubleshooters organize their models around the causal interactions in the electrical system rather than the linear organization of the wiring. David recommends representing the functional organization of the system (how modules interact showing paths of interaction) so novices learn to trace paths of causality, not the physical wire itself. When troubleshooting electronics problems, novices focused on power distribution and the physical layout of radar, whereas experienced troubleshooters used their understanding of the flow of information (Tenney & Kurland, 1988).

Although both topographic and functional representations of relationships provide the troubleshooter with paths to trace while generating hypotheses, novice troubleshooters are more likely to use topographic search strategies, whereas experienced troubleshooters more commonly use functional representations when troubleshooting (Hoc & Carlier, 2000; Rasmussen, 1984a). Troubleshooting strategies based on functional knowledge of the operation of the device lead the troubleshooter to the problem more efficiently.

What Kinds of Performance or Procedural Knowledge Are Necessary?

Performing troubleshooting tasks, such as measuring voltage or fuel pressure, conducting tests, and making observations of the operation of different parts, involves procedures that must be known and practiced. Knowledge of these activities allows troubleshooters to carry out the operations for performing routine maintenance procedures or testing the components during the troubleshooting process (Hegarty, 1991). Procedural knowledge is specific to the system and the tools used to troubleshoot it. Therefore, its application is limited to that particular content or system (Schaafstal & Schraagen, 1993). Traditionally, mechanics were required to know how to use voltmeters and pressure gauges to test automotive components. Today, they attach engine sensors to a computer that automatically tests the engine's functions.

What Kinds of Strategic Knowledge Are Necessary?

According to Johnson et al. (1995), strategic knowledge plays an essential role in troubleshooting by reducing the problem space, isolating the potential faults, and testing and evaluating hypotheses and solutions. Knowing what part of the electrical systems to test first when diagnosing a car that will not start is important strategic knowledge. Strategic knowledge helps the troubleshooters confirm the hypotheses and solutions they have generated or seek new alternatives when the existing hypotheses or solutions are confirmed false or unfeasible. Schaafstal and Schraagen (1993) classified strategies used in the troubleshooting process as global strategies or local strategies. Global strategies are independent of specific domain content or system and can be applied across different domains. Local strategies are the ones that are only applicable to a specific content domain or system.

Global strategies help the troubleshooter reduce the problem space whereas local strategies help the troubleshooter conduct the reduction process.

The most common, albeit not most successful, global troubleshooting strategy is the serial elimination strategy (start with component nearest the troubleshooter and trace backwards or forward through the system). Because of its inefficiency, this strategy is seldom, if ever, recommended. Johnson (1991) and Brown, Burton, and deKleer (1982) identified five commonly used global strategies in the troubleshooting process.

1. **Trial and Error**: Randomly attack any section of the system where the possible fault might have occurred. This strategy is most common in the performance of novice troubleshooters.
2. **Exhaustive**: List all the possible faults and test them one by one until the actual fault is identified. This strategy, similar to serial elimination, is practical only in simple systems.
3. **Topographic**: Isolate the fault through identifying a series of functioning and malfunctioning checks following the traces through the system. The topographic strategy is usually implemented in two ways, forward or backward. The forward topographic strategy starts the troubleshooting procedure at a point where the device is known to be functioning normally and then works toward the fault by following the system. The backward topographic strategy follows the same procedure but starts at the point of malfunction and then works backward to the input point (Johnson et al., 1995; Newell & Simon, 1972).
4. **Split Half**: Split the problem space in half and check the functioning condition to determine in which half the fault is located. This method reduces the problem space by confirming the faulty section. The procedure is repeated until the potential faulty area is reduced to a single component. This strategy is efficient when the faulty system is complex and the initial problem space appears to contain several potential faults with no strong indication of where the actual fault lies (David, 1983). In medical diagnosis, this is known as the differential diagnosis.
5. **Functional/Discrepancy Detection**: Isolate the fault by looking for the mismatches between what is expected in a normal system operation and the actual behaviors exhibited (Brown et al., 1982). By detecting the mismatches, the troubleshooter can identify the components where the difference is located and, in turn, isolate the actual fault. Performing this strategy requires a

thorough integration of system knowledge (especially the interrelationship between functional knowledge and behavioral knowledge).

Little research has compared the effectiveness of domain-general vs. domain-specific troubleshooting strategies. Konradt (1995) showed that domain-general strategies, such as split-half and uncertainty rejection, play only minor roles in real-life troubleshooting. Experienced troubleshooters rely more on case-based strategies (addressed next), especially in routine failures. Troubleshooting is clearly domain- or context-specific.

HOW IS EXPERIENTIAL KNOWLEDGE RELATED TO TROUBLESHOOTING?

Research studies have confirmed that experience is the most common determinant of expertise and that the recall of historical information is the most frequent strategy for failure diagnosis (Konradt, 1995). Bereiter and Miller (1989) found that troubleshooters base their diagnosis on their beliefs about the cause once a discrepant symptom is found. Those beliefs are based on historical information (i.e. experience). They also found that the most common reason for taking a particular action during troubleshooting is to test for the most common problem based on experience. Automobile mechanics, for example, often shorten their diagnostic process by applying their historical knowledge of specific fault tendencies in certain models or vintages of cars.

Because of the importance of experiential knowledge, it is essential that learners be required to practice troubleshooting tasks. Kyllonen and Shute (1989) recommend troubleshooting a simulated task or "walking through" a performance. With extensive practice, troubleshooters construct event schemas and rely more on historical information based on experience than they do conceptual knowledge. Later in the chapter, I describe the role of a simulator to provide case-based practice.

WHAT MENTAL CAPACITIES SUPPORT TROUBLESHOOTING?

In addition to different knowledge states, there are individual, mental differences in experience, cognitive abilities, aptitudes, and cognitive styles related to troubleshooting performance (Morris & Rouse, 1985). Research has focused on three of those differences: working memory capacity, causal reasoning, and analytical reasoning (field independence).

How Is Working Memory Related to Troubleshooting?

Working memory is a short-term memory store that enables humans to access and temporarily store information needed to complete a task. Working memory was a predictor of troubleshooting performance (Axton et al., 1997). Troubleshooting performance degrades when working memory is exceeded, which imposes greater cognitive load on the learner (Cooper & Sweller, 1987; Sweller & Cooper, 1985). Cognitive load is intrinsic to the processing demands of the task (Mayer & Moreno, 2003; Paas, Renkl, & Sweller, 2003). The primary cause of cognitive overload is system complexity (Perez, 1991). As systems become more complex, troubleshooting problems place more demands on working memory and therefore became more difficult to troubleshoot (Allen, Terague, & Carter, 1996). More time is required to solve the problems because learners take more actions and repeat more tests. In Chapter 9, I describe the use of worked examples as an antidote to some aspects of cognitive load.

How Is Causal Reasoning Related to Troubleshooting?

Causal reasoning describes the cognitive abilities required to understand the co-occurrence of cause–effect relationships (Kelly, 1973) and the mechanisms responsible for linking the cause to the effect (see Chapter 17 for more detailed descriptions of causal reasoning). Causal reasoning enables learners to make predictions, to explain relationships, and to infer causes. It is an essential skill in solving any kind of problem involving multiple, interacting components, such as identifying causes of discrepancies in system states in order to troubleshoot (Axton et al., 1997). Perkins and Grotzer (2000) found that students engaged in any kind of meaningful learning must move beyond their simplified causal reasoning habits.

How Is Analytical Reasoning Related to Troubleshooting?

Analytical reasoning is another important cognitive capacity for troubleshooting. Analytical reasoning is most often described as field independence, which describes the extent to which the surrounding perceptual field influences a person's perception of items within it. Non-analytical people (field dependents) find it difficult to locate the information they are seeking because the surrounding field masks what they are looking for. Analytical reasoners (field independents) are more adept at disambiguating information from its surrounding field and therefore are better problem solvers because they are better able to isolate task-relevant information (Heller, 1982; Ronning, McCurdy, & Ballinger, 1984). In a study of Irish apprentice electricians, Moran (1986) found that among several individual difference variables, field independence was most highly correlated with fault diagnosis and its strongest predictor. This is because analytics (field independents) are more efficient hypothesis testers than field dependents while learning and solving problems (Davis & Haueisen, 1976).

HOW HAS TROUBLESHOOTING BEEN HISTORICALLY TAUGHT?

Because troubleshooting is so commonly performed, many instructional approaches have been used to educate troubleshooters. Unfortunately, many of those approaches are based on misconceptions and out-of-date beliefs about teaching troubleshooting. For example:

- Algorithmic troubleshooting is an adequate model.
- General problem-solving strategies are efficient and effective.
- Experts prefer to use hypothetico-deductive problem solving.
- The scientific method (as usually represented in introductory textbooks) is a good model for problem solving, including troubleshooting.
- General reasoning ability is more important than domain knowledge.
- If you're good at diagnosing one kind of problem, you're good at diagnosing other kinds.

These beliefs are now understood to inhibit expertise development. In fact, they often cause damage.

How Have Procedural Demonstrations Been Used?

The default instruction for troubleshooting is to demonstrate a sequence of troubleshooting actions. Students receiving procedural training (step by step) performed more accurately and conducted more correct checks than students who received instruction on the system structure (Swezey, Perez, & Allen, 1988). However, students receiving instruction about the system structure transferred their learning better than the learners receiving procedural instruction. Demonstrating a sequence of actions can improve performance on the modeled task, but those gains do not transfer to other tasks (Morris & Rouse, 1985). Students following a fault-isolation manual that demonstrated required continuity checks on cables, meter reading, switch setting, and device replacement encountered information overload and were unable to explain why they performed the steps (Kurland, Granville, & MacLaughlin, 1992). Students learn from procedural demonstrations by reproducing operations. If those specific operations fail to reveal the fault, learners who are taught procedurally do not know what to do. They lack the domain principles, system knowledge, and strategic knowledge required to transfer their troubleshooting.

How Has Conceptual (Content) Instruction Been Used?

Content approaches to teaching troubleshooting emphasize theoretical and conceptual understanding of the system, removed from any troubleshooting activity. Unfortunately, conceptual understanding of the system alone does not support fault finding (Morris & Rouse, 1985). Students receiving only content instruction perform more slowly, make more errors, and are less successful in troubleshooting (Morris & Rouse, 1985). Schaafstal et al. (2000) found that instructors who teach conceptual content could not troubleshoot or transfer their skills from one radar system to another. Their trainees understood details of system but were unsystematic in their troubleshooting approach.

When used in combination with practice, content instruction should use a breadth-first organization of instruction that starts with an overview and covers the functions of subsystems before describing subsystem components (Zeitz & Spoehr, 1989). The organization of content affects learners' knowledge representation and the degree to which information can be applied in practice.

Related research indicates that the ways that people have learned system-related concepts depends on the job that people perform. Flesher (1993) compared the understandings of design engineers and maintenance technicians and found that designers' understanding emphasizes theoretical concepts when compared with maintenance technicians who actually troubleshoot the systems. In fact, Johnson (1989) found that designers required longer to troubleshoot problems than novices because they were sidetracked by what they perceived as design flaws. As indicated before, troubleshooters and designers have fundamentally different approaches to troubleshooting. Flesher concluded that theory-based approaches to instruction for troubleshooting are not the most effective.

How Have Rule-Based Approaches Been Used?

Another prominent approach to teaching troubleshooting requires learners to follow a set of rules for troubleshooting, such as decision trees, flow charts, or rule-based expert systems that model a series of decisions that troubleshooters use in order to detect faults. These decision aids are often presented as job aids or just-in-time instruction. For example, most manuals for new appliances have a troubleshooting section that lists a number of possible faults that are associated with various actions for ameliorating those faults. Those methods assume that the user can recognize various fault states and know how to perform the actions specified in the manual (wishful thinking under most circumstances). More sophisticated approaches have been tested. Rouse, Pellegrino, and Rouse (1980) developed an expert system rule base for selecting tests when diagnosing three different tasks and compared it with human performance. When they used their rule base as training, negative transfer resulted. Although novices prefer following rules (Konradt, 1995), learners are not conceptually engaged when they apply rules; they develop inadequate mental models of the system that are required for far transfer.

Other research shows that in troubleshooting practice, rule sequences are abandoned by troubleshooters. When taught how to use search algorithms in real-word diagnostic settings, humans resorted to ad-hoc hypotheses (Hoc & Carlier, 2000). Also, it is difficult to reduce an expert technician's actions and knowledge to a set of rules. Experts can easily decide what to do, but they are much less able to provide explicit rules about why they performed as they did (Means & Gott, 1988; Morris & Rouse, 1985). Learners who learn to troubleshoot by following rule-based decision aids lack the domain, device, procedural, and alternative forms of experiential knowledge required to become effective troubleshooters.

How Have Simulations Been Used?

Troubleshooting instruction often provides necessary practice on simulations of the system being learned. Johnson and Rouse (2001) found that practice on computer simulations resulted in learning that was comparable to traditional lecture and demonstration methods. Much earlier, Johnson and Norton (1992) concluded that simulators alone are insufficient for learning to troubleshoot (a conclusion that is central to the troubleshooting instruction model presented later in this chapter).

The most prominent issue related to simulator training (although not necessarily the most important) has been the fidelity of the simulation. Johnson and Norton (1992) showed that low-fidelity simulator training should be combined with real equipment or a high-fidelity simulation in order to support learning. Novices need practice on simulators with reasonable fidelity in order to transfer their troubleshooting skills to real equipment. Students trained on simulators with high physical and functional fidelity were able to reach correct solutions more quickly than students using lower fidelity simulators, and they repeated fewer tests (Allen, Hayes, & Buffardi, 2001). Functional fidelity is an important determinant of performance.

The most important issue related to fidelity is how accurately the simulator reflects the dynamic interactions within the system. Static simulations of systems are inadequate. In their study of electronics troubleshooting, Park and Gittelman (1992) found that an animated simulator resulted in shorter learning times and fewer trials than a static simulator. Performance on simulators predicts transfer performance on equipment to the degree that the same skills are required (Morris & Rouse, 1985). Therefore, it is essential that transfer of training be evaluated using actual equipment, at least for the final training. Airline pilots use highly sophisticated simulators to become certified to fly new aircraft.

How Have Intelligent Tutoring Systems Been Used?

Numerous military-funded projects developed intelligent tutoring systems (ITSs) to teach troubleshooting. These complex systems usually apply an artificial-intelligence formalism (e.g., expert systems, neural nets) to represent how an expert thinks (expert model), how a learner performs (student model), and how the instruction should be adapted to the learner's progress (tutorial model). The student model is used to recommend instructional adaptations to individual performance and to predict actions of the student based on analysis of a particular problem state (Gitomer, Steinberg, & Mislevy, 1995). Gitomer et al. (1995) built the Hydrive ITS, in which the student model has three components:

1. **action evaluator** (assesses actions in simulation);
2. **strategy interpreter** (assesses strategic understanding, looking for examples of space-splitting, serial elimination, and remove and replace strategies);
3. **student profile**.

Other examples of ITSs developed to support troubleshooting include Qualitative Understanding of Electric System Troubleshooting (QUEST; Feurzig & Ritter, 1988); Framework for Aiding Understanding of Logical Troubleshooting (FAULT); and MACH-III on radar troubleshooting (Kurland et al., 1992). Mach-III provided animated, physical, and functional diagrams that provide multiple views at different levels; a troubleshooting tree that organizes procedures in functional hierarchy; a troubleshooting adviser that guides mechanics; and an explanation system that provides background information.

ITSs have had different effects on learning to troubleshoot. Johnson et al. (1993) developed a technical troubleshooting tutor that supported two troubleshooting activities: problem-space construction and fault diagnosis. They found that students working on the tutor had a 78% improvement in troubleshooting performance with only 19% more practice. Another well-known tutor was SHERLOCK, a computer-coached practice environment for teaching avionics troubleshooting. Its instructional model was based on dynamic assessment of the learner while troubleshooting problems (Lajoie & Lesgold, 1992a). Trainees who used SHERLOCK for twenty hours over two weeks performed as well on troubleshooting tasks as experienced technicians (Gott, Hall, Pokorny, Dibble, & Glaser, 1993).

ITSs can be effective for training troubleshooters, but there are limitations. Most ITSs base their solution paths on an expert model that provides feedback when the learner performs a discrepant action. However, expert models in ITSs do not account for fundamental differences in the ways that novices and experts represent the devices being troubleshot or the diverse strategies that may be used to approach problems, let alone the differences in how experienced or expert troubleshooters conceive the system and perform. ITSs are also very expensive to build and are system-specific, so they are not applicable to other systems.

Although numerous instructional approaches for preparing troubleshooters have been developed and researched, none of these instructional approaches have integrated the different knowledge states (especially experiential or historical knowledge) and capacities necessary for learning to troubleshoot. The purpose of this chapter is to describe a model for designing environments for learning how to troubleshoot that integrates the different knowledge states required to become a proficient troubleshooter. Those environments are based on a cognitive model of troubleshooting, which is described next.

HOW SHOULD PEOPLE TROUBLESHOOT?

The simplest conception of troubleshooting is to find the faulty component in a device and repair or replace it (Perez, 1991); however, that conception is too simplified, especially for tasks such as medical diagnosis. Troubleshooting requires generating and evaluating hypotheses (Johnson, 1989) and taking corrective action (Schaafstal et al., 2000). According to Schaafstal and Schraagen (2000), troubleshooting consists of four subtasks:

1. Formulate problem description.
2. Generate causes.
3. Test.
4. Evaluate.

According to Johnson et al. (1993), troubleshooting is an iterative process of generating and testing that consists of four sub-processes:

1. problem-space construction;
2. problem-space reduction;
3. hypothesis generation or testing (fault isolation or diagnosis process);
4. solution generation or verification.

While troubleshooting, performers:

- use many observations in a sequence of simple decisions;
- use general search procedures that are not dependent on actual system or fault;
- search to find faulty components;
- search thorough systems to identify appropriate subsystem, state or component.

(Rasmussen, 1984a)

According to Axton et al. (1997), troubleshooting includes three phases:

1. inspection (assessment of the effectiveness of a system by evaluating changes in the characteristics of the system's outputs or components;
2. troubleshooting (a search for the components of the system producing substandard outputs cause);
3. a search for actions that will fix the discrepancy (cause-behavioral sequence relations or repair).

None of these conceptions, however, addresses the role of previous experience, which is the most frequent strategy for failure diagnosis (Konradt, 1995). Experienced troubleshooters are most efficient because they call on event schemas that are based on the problems they have solved before. So, in order to learn how to troubleshoot, students must learn how to accomplish the following tasks.

How Do We Construct a Problem Space for Troubleshooting?

Constructing problem space is the first step in solving problems (Newell & Simon, 1972). "Problem solving must begin with the conversion of the problem statement into an internal representation" (Reimann & Chi, 1989, p. 165). The problem space of any troubleshooting problem is the mental model of the task environment that the troubleshooter constructs. That model should represent the goal state of the system, the normal states of the system and system components, various fault states, the system structure (including the components of the system and the relationships among the components), the flow control, and a number of potential solution paths (including the most viable one and the possible alternatives). A major difference between proficient and inexperienced repairmen is their ability to conceptualize the problem space (Gitomer, 1988). The best auto-mechanics possess rich representations of subsystems for each model and vintage of car they diagnose, and they frequently cite specific fault tendencies for each.

Because they lack system knowledge, novice troubleshooters usually rely on external problem representations. External problem-space representations may include flowcharts, schematic diagrams, or functional flow diagrams (Johnson & Satchwell, 1993). Automotive systems are represented as wiring diagrams, exploded views of mechanical systems, and flowcharts of diagnostic procedures. External problem-space representations help novice troubleshooters construct internal representations of the system. Later, we describe a multi-layered external problem representation for helping learners that includes topographic description of the system components, functional descriptions of the system flow, normal behaviors of the system components, symptoms or behaviors the system exhibit when operating correctly and faultily, and representations of strategic decisions required during troubleshooting.

Constructing a mental problem space helps troubleshooters to isolate the sub-system, component, or device in which the fault is located more efficiently (Frederiksen & White, 1993). Highly proficient troubleshooters mentally represent the operations of the system in its normal and faulty states (Axton et al., 1997). Because troubleshooters (including both experts and novices) tend not to question their initial problem space once it is established (Johnson et al., 1993), it is essential that learners verify their conceptual understanding whenever troubleshooting actions are taken. Because of rapidly changing systems in automobiles and system differences between different manufacturers, auto-mechanics must generate the correct representation of the automobile being diagnosed. Mechanics specialize their work on specific models or manufacturers because they need to construct fewer problem spaces of those complex systems.

How Do We Identify Fault Symptoms?

Based on the normal and fault states for system components represented in the problem space, troubleshooters must learn to seek out and recognize faulty components by seeking discrepancies between normal states and existing states of system components (also known as gap analysis). Effective troubleshooters use their mental model of the functioning system and mentally add faults to it and predict the misbehavior that would result (or recall similar stories). Then, after ranking by probability and cost, they perform tests to confirm the expected data. Recognizing symptoms of faulty components is also aided by experience. The likelihood of symptoms becoming apparent is a function of historical knowledge.

How Do We Diagnose Fault(s)?

After constructing a problem space, the troubleshooter begins the diagnosis process by examining the faulty system and comparing the system states to similar problems that she or he has solved. If a previous problem is recalled, the problem space is reduced immediately to include a description of the old problem. Experienced troubleshooters categorize problems based on prior experiences. After asking only one question, my mechanic once diagnosed a faulty air-flow meter, because those meters are historically the source of problems with the type of automobile being diagnosed. Once, I interviewed an airline maintenance worker attending to a delayed flight, who generated a correct hypothesis about an electrical problem on a DC-9 based on a single symptom, because he "had been working on them for twenty-five years." The first thing that any experienced troubleshooter does when encountering symptoms is to recall experiences with similar symptoms.

If a previous problem is not remembered and therefore cannot be reused, then the troubleshooter must generate hypotheses by analyzing the initial information collected in order to identify discrepancies between existing states and normal states and by interpreting those discrepancies based on their conceptual model of the system components. Johnson et al. (1995) reported that the difference between high and low proficient troubleshooters is their ability to correctly interpret the symptoms they have identified. Experts form their initial hypotheses based on the preliminary information acquired during the construction of problem space and the subsequent interpretation (MacPherson, 1998). Newell and Simon (1972) contended that this interdependence is crucial for distinguishing task-relevant and task-irrelevant components within the system. Through this process, initial reduction of the problem space can be achieved by identifying and excluding task-irrelevant components. The next phase is to generate and test potential hypotheses.

Throughout the process of "hypothesis generation and testing" cycles (Johnson et al., 1995, p. 10), the troubleshooters attempt to further narrow the problem space and to isolate the potential faults. Johnson (1989) explained that these potential hypotheses are generated to provide possible explanations for the causes of the system fault. Johnson et al. (1995, p. 10) classified hypotheses into four levels:

1. **System**: The hypotheses conjecture the fault at the system level but do not reduce the problem space beyond the entire equipment or complete system.
2. **Subsystem**: The hypotheses conjecture the fault at the subsystem level and reduce the problem space to a discrete subsystem within the complete system.
3. **Device**: The hypotheses conjecture the fault at the device level and reduce the problem space to a limited number of components within a subsystem.
4. **Component**: The most specific type of hypotheses that conjecture the fault at the component level and result in the identification of a single component as the potential fault cause.

When all potential hypotheses are generated, these hypotheses have to be tested and evaluated (Elstein, Shulman, & Sprafka, 1978). Subsequent research on medical diagnosis challenged this model. Physicians actually base their diagnoses much more on pattern recognition of prior experience. The hypothetico-deductive model that Elstein proposes is actually rather rare. Another approach to data reduction is after making an initial evaluation, Schaafstal and Schraagen (1993) suggest that troubleshooters prioritize the hypotheses for testing and evaluation based on the likelihood of being the cause of the fault and the interdependence level between the component and the symptoms. The process of isolating the fault is a search through the entire system from subsystems and devices, to components in a hierarchical manner in order to identify the cause of the fault.

The process of testing hypotheses is not always linear and straightforward. Rather, it is iterative and recursive. At each level, two possible scenarios may occur. If the high-level hypothesis is correct, then the troubleshooter must be able to continue generating more specific hypotheses about narrower sections of the system until the specific faulty component is found. For example, if a mechanic diagnoses a problem in the fuel system, he or she must generate and test hypotheses about which section of the fuel section is faulty. On the other hand, if the initial, high-level hypothesis is confirmed as incorrect, then the troubleshooter must detect that he or she is heading in the wrong direction and amend the hypothesis and reasoning. Therefore, the ability to evaluate and adjust one's own hypotheses and testing procedures throughout the diagnostic process is critical to becoming an effective troubleshooter. As MacPherson (1998) discovered, when experts found their hypothesis was incorrect, they quickly discarded the false hypothesis and replaced it with an alternative based on the testing results. A key for troubleshooters in using tests results to evaluate their own hypothesis testing process and modifying it if necessary (Means & Gott, 1988).

How Do We Generate and Verify Solutions?

The process of solution generation and verification is similar to hypotheses generation and evaluation, although it has not been researched nearly as extensively. The troubleshooter needs to generate one or more solutions for repairing the system based on the results of tests. The simplest solution is to replace a part or module. In many troubleshooting circumstances, that is the preferred solution because it requires the least time. Many contemporary systems are designed so that modules can be easily replaced, because the modules cost less than the troubleshooter's time.

If more than one solution option is generated, then the troubleshooter must select and validate the preferred solution. As with diagnosis, skilled troubleshooters rely first on their experiences. They know that certain solutions are quicker, easier, cheaper, or more reliable. For inexperienced troubleshooters, the solution generation/validation is also an iterative process. The troubleshooter must select the most plausible solution from the set of solutions generated (Johnson et al., 1993) and determine which best meets all the constraints (e.g., effectiveness, efficiency, system-specifics, or economic consideration). Inexperienced troubleshooters often implement and then test the effectiveness of different solutions. Based on the test results, the inexperienced troubleshooter accepts or rejects the selected solution. This is not the most efficient method of troubleshooting. Experience should eliminate the need for iterative testing.

During the solution-evaluation process, the troubleshooter may find that additional information is needed for confirming or disconfirming the selected solution (Frederiksen, 1984). Information may even cause the troubleshooter to reject or modify the original hypothesis or even to revise the initial problem space. Thus the troubleshooting process is recursive throughout the four phases with adjustment or modification as needed (Johnson, 1989). The solution generation and evaluation process is an essential characteristic in effective troubleshooting (Johnson et al., 1993).

Should We Remember Troubleshooting Experiences?

The final step is implicit. Troubleshooters add each troubleshooting experience to their personal case library of experiences. The more difficult or unusual the problem solved, the more likely the problem is remembered (Jonassen & Hernandez-Serrano, 2002), precisely because the case reveals some new truth about the functional model of the system.

WHAT ARE THE COMPONENTS OF A TROUBLESHOOTING LEARNING ENVIRONMENT?

Based on the foregoing conception of troubleshooting, I propose the following model for designing troubleshooting-learning environments (TLEs) to support learning how to troubleshoot (see Figure 4.2). The model describes a multi-layered system model, a simulator, and a case library and two instructional components (worked examples and practice).

The TLE model assumes that the most effective way to learn to troubleshoot is by solving troubleshooting problems. The environment presents learners with symptoms and states of cases as problems to solve (Chapter 8), a simulator (Chapter 14) for testing actions, a case library of prior experiences (Chapter 12), and a multi-layered model of the system being troubleshot (Chapter 19). The key to the TLE is that it provides just-in-time instruction. Rather than teaching students all

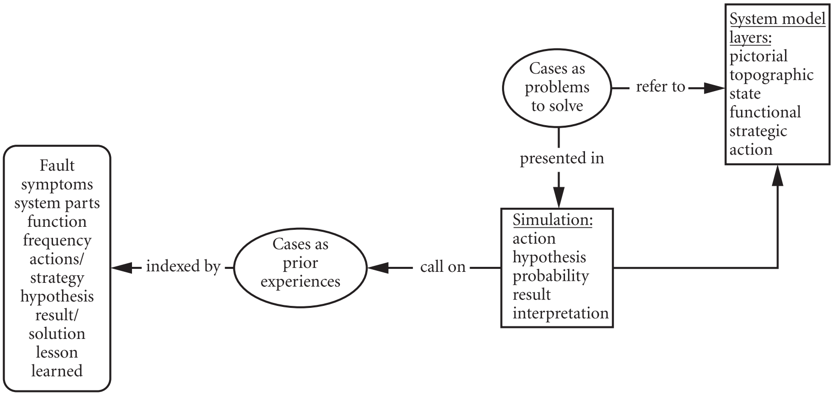


Figure 4.2 Components of troubleshooting learning environment.

of the content knowledge that they may need to possess prior to requiring them to troubleshoot a new problem, conceptual instruction is provided by the system model. This does not mean that students are necessarily complete novices, having received no content instruction. In fact, we do not know how much content instruction is required for using the TLE. That can only be ascertained through experience and empirical research. However, the most important component of the TLE is the novel, authentic problems that require troubleshooting.

What Is a System Model?

Because novices, advanced beginners, and even competent performers rely on functional understanding of the domain in order to generate hypotheses, it is important that they integrate the different kinds of knowledge of the system being troubleshot into a coherent mental representation. In a series of studies, Kieras and Bovair (1984) showed that a device model illustrating the specific configuration of the components and controls in a device enables learners to infer procedures and learn to operate a device more rapidly. The system model allows learners to view how the system functions (including normal functioning and malfunctioning states) so they can make reasoned diagnoses (which components to test/evaluate based on which hypotheses/solutions). Learners mentally construct problem spaces by selecting and mapping specific relations from a problem domain onto the problem (McGuinness, 1986). In order to do that, multiple kinds of knowledge must be represented in different ways. Rasmussen (1984a) recommended a hierarchy of information types that are needed to diagnose a system, including:

- **functional purposes** (production flow models, system objectives);
- **abstract functions** (causal structure, information flow topology);
- **generalized function** (standard functions and processes, control loops);
- **physical functions** (electrical, mechanical, chemical processes of components);
- **physical form** (physical appearance and anatomy, material, and form).

Johnson and Satchwell (1993) showed that providing functional flow diagrams during instruction improved overall system understanding and conceptual understanding of causal behavior. Those diagrams should be simple, showing only the essential components of the system (Johnson & Satchwell, 1993). Therefore, we recommend a system model that integrates multiple, simpler representations of the system that overlay each other. While inspecting any system component on one level, learners can zoom in or out to other layers.

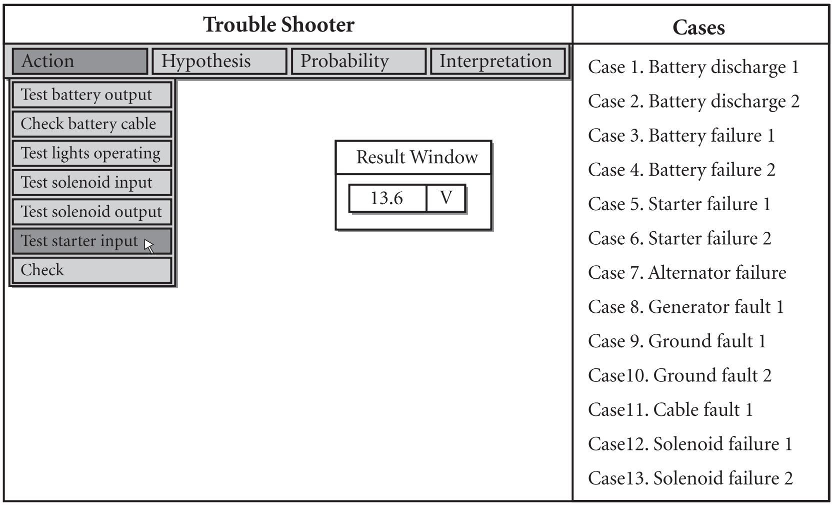
- **The pictorial layer** contains pictures of the device or system as it exists. Associating representations of the system with the actual system is important (Allen et al., 2001; Johnson & Norton, 1992). Depending on the complexity of the system, pictures of different parts of the system may be necessary. Zooming in from the pictorial layer reveals the topographic layer.
- **The topographic layer** illustrates the components of the system, their locations, and their interconnections. Topographic representations are important because experts search for faulty components by means of topographic representations of the system (S. Johnson, 1988; Rasmussen, 1984a). Zooming in from the topographic layer reveals the state layer.
- **The state layer** provides several overlays to the topographic layer. One overlay conveys normal states or values for each component. These values enable the troubleshooter to compare actual with normal values in order to determine whether any component is malfunctioning (Patrick, 1993). The symptom overlay conveys symptoms associated with each component malfunction. The probability overlay conveys probabilities of malfunctions or fault states. Being able to match existing symptoms and probabilities with a set of stored symptoms and probable fault states represents a common approach to fault finding (Patrick, 1993). However, Patrick showed that over-reliance on symptoms may result in "tunnel vision" obscuring alternative hypotheses, so the strategic layer provides alternate strategies for diagnosing faults. If the troubleshooter is unaware the alternative actions, he or she can zoom in on the strategic layer.
- **The functional layer** illustrates and describes the information, energy, or product flows through the system and how the components affect each other. Understanding system functions is more effective than strategic advice (Patrick & Haines, 1988); however, the combination should be more effective. The learner can zoom from the functional to the strategic layer to identify optional actions and tests.
- **The strategic layer** consists of rule-based representations of alternative decisions regarding the states described on the state layer. This layer consists of diagnostic heuristics that support fault finding (Patrick & Haines, 1988). Research is needed to determine which method would provide better strategic support during

diagnosis. Finally, zooming in from the strategic layer reveals the action layer.

- **The action layer** includes descriptions of procedures for conducting various tests or operations. The primary purpose of this layer of information is to serve as a job aid or just-in-time instruction for students performing various tests or other actions.

How Does the Simulator Work?

The heart of the TLE is the simulator (see Figure 4.3 and Chapter 14). This is where the learner gains experience troubleshooting. The simulator is based on the PARI (precursor, action, result, interpretation) system of analysis (Hall, Gott, & Pokorny, 1995). After processing a description of the problem to solve including the behavior and symptoms of the device being troubleshot, the learner (like an experienced troubleshooter) first selects an action using the pull-down menu at the left of the screen, such as ordering a test, checking a connection, or trying a repair strategy. The novice may be coached about what action to take first based on the symptoms or may select any action. The learner may access the system model at any time in order to see the system and its components function in their normal states, strategic rules for when and how to observe or test the components, how to perform those actions, and the multi-modal results from such actions. Each action taken by the troubleshooter is associated with the corresponding system component in the system model.



Result Window

13.6 V

Figure 4.3 The simulator in the TLE.

For each action that the learner takes, the learner is required to select a fault hypothesis that he or she is testing using the pull-down menu to the right of the action menu in the simulator. This is an implicit form of argumentation requiring the learner to justify the action taken. If the hypothesis is inconsistent with the action, then feedback is immediately provided questioning the rationale for taking such an action. The troubleshooter must also predict the probability that the hypothesis he or she has chosen is actually the fault.

Troubleshooters at all skill levels have difficulty using probabilistic information (Morris & Rouse, 1985). Providing practice in predicting probabilities also acts as a metacognitive prompt depicting the troubleshooter's certainty in hypothesis selection. If the hypothesis or probability is inconsistent with normal states, feedback is provided in a pop-up window and the troubleshooter is required to select another probability. If the hypothesis and probability selected are within normal boundaries, the troubleshooter sees the results of that action in the results window. Those results may be voltage values, pressure readings, temperature, color of an item, or any other relevant description. The troubleshooter must observe the values in the results window and then select an interpretation of those results using the pull-down menu. An interpretation that is inconsistent with results will also prompt feedback that requires the troubleshooter to select another interpretation.

The simulator is structured to be constructive and performance based. Learners must construct a prediction (a kind of theory) about why the system is not functioning properly) based on system characteristics and then test that theory. Rather than learning about troubleshooting, the learner is engaged in a cognitive apprenticeship (Brown, Collins, & Duguid, 1989) with a normal troubleshooter. In most troubleshooting tutoring systems, providing feedback usually refers to giving an informative explanation about the correctness of the learners' actions or responses (Frederiksen & White, 1988). In this troubleshooting architecture, the troubleshooter gains competence in interpreting the feedback from the system itself. In real work settings, troubleshooters cannot rely on the feedback from coaches or tutoring systems to see if they are pursuing an appropriate diagnosis. Rather, as Means and Gott (1988) suggested, the troubleshooters need to make decisions for how to proceed to the next step in the troubleshooting process based on the behavioral reactions (feedback) that the system exhibits after the test procedures are completed. In order to troubleshoot independently and competently, troubleshooters must make such judgments on their own.

Second, the simulator enables dynamic assessment of learner performance (Lajoie & Lesgold, 1992b). The actions that a learner takes and the reasons for those actions, both in terms of the hypothesis and interpretation selected, can provide a model of the learner's understanding of the system. The simulator provides clear measures for assessing and evaluating a learner's competence. The number of steps and accuracy of hypotheses and interpretations provides quantitative information about a learner's performance and understanding.

Third, the learner is gaining troubleshooting experience while learning. The results of practice are added to the learner's case library of fault situations, so that the learner can learn from personal experience. Case libraries are described next.

What Is a Case Library and How Does It Help?

If the simulator is the heart of the TLE, then the case library is the head (memory) of the TLE. Experts' knowledge is primarily derived from cases and concrete episodes (Konradt, 1995); that is, experts use case-based strategies where symptoms observed in previous situations are collected and compared with those in similar and current situations (see Chapter 12 for a more detailed description of case libraries and case-based reasoning). The case library is in effect a database of system faults that contains stories of as many troubleshooting experiences as possible. Each case represents an indexed story of a context-specific troubleshooting experience. Among technicians, the primary medium of discourse is stories (Jonassen & Henning, 1999). The case library consists of stories about how experienced troubleshooters have solved similar problems that are indexed and made available to learners. Be sure that the case library include faults in all area of the system, not just the high-frequency cases.

WHAT INSTRUCTIONAL SUPPORTS ARE INCLUDED ON THE TLE?

In order to help learners use the TLE, we recommend two essential instructional supports: worked examples and practice.

How Are Worked Examples Used?

Worked examples illustrate how to use the TLE and also model different troubleshooting strategies (see Chapter 9 for more detail on worked examples). If the TLE is entirely online, a pedagogical agent reads the problem symptoms and models strategies for identifying the fault state and symptoms, constructing a model of the problem space or accessing the system model, examining the faulty sub-system, recalling from previous cases, ruling out least likely hypotheses, generating and testing hypotheses, interpreting results, and so on. The agent also models how to relate the problem symptoms to system components and relate system components in the troubleshooter to system components in the system model.

Worked examples reduce the heavy cognitive load imposed by the TLE. Integrating multiple representations in the systems model with the experiences of others while also manipulating the simulator imposes heavy demands on working memory (Paas et al., 2003). Worked examples are useful for several reasons. First, splitting attention between multiple information sources interferes with students' acquisition of schemas representing domain concepts (Mwangi & Sweller, 1998; Tarmizi & Sweller, 1988). Integrating those representations in a multilayered model reduces that effect. Second, effective worked examples should highlight the subgoals of the problem (Catrambone & Holyoak, 1990). In the case of troubleshooting, those subgoals include identifying fault symptoms, constructing a system model, diagnosing the fault, generating and verifying solutions, and adding experiences to the personal library. This latter subgoal is a form of self-explanation that reduces the need to look back at examples and improves performance (Chi, Bassock, Lewis, Reiman, & Glaser, 1989; Chi & Van Lehn, 1991). Worked examples should be used more heavily in the initial stages of skill development (Renkl & Atkinson, 2003). In the latter stages, problem-solving practice is superior because intrinsic cognitive load decreases. Cognitive load decreases as learners develop solution schemas or scripts. As these schemas are constructed, learners better index knowledge and reduce cognitive load even more.

What Kind of Practice Is Required?

Practice consists of using the simulator to troubleshoot new problems. During practice, new problems are presented to the learner, who uses the simulator to isolate the cause of the fault. The learner may access the system model or case library in order to understand a system function, determine normal states, or get advice form an experienced troubleshooter. Questions may be inserted (see Chapter 18) to scaffold thinking about the system functions and states. The number of practice problems required to develop different levels of troubleshooting skill is not known. That will depend on the complexity of the system being troubleshot, the abilities and dispositions of the learners, and a host of individual differences. It is worth noting that every action that learners take during their practice can be captured and assessed. The purpose of that assessment may be to track progress during learning or merely to see if the learner is mindfully engaged in the learning process.

Normally, a simple-to-complex practice sequence is recommended. When troubleshooting problems are practiced in a random order, causing high inter-task interference, far transfer improves but not near transfer (De Croock, van Merrienboer, & Paas, 1998). Learners constructed richer schemata for the system they were troubleshooting, which provided faster, more accurate diagnoses because the learners invested more mental effort during practice. Van Merrienboer, Kirschner, and Kester (2003) recommend two kinds of whole task scaffolds, simple-to-complex versions of the task in order to decrease intrinsic cognitive load and starting with worked examples in order to decrease extraneous cognitive load.

HOW EFFECTIVE WILL THE TLE BE?

The easy answer to this question is that we do not know. A TLE has never been built and tested, although most of its components have. Predictions of success are based on the necessity of integrating experience, conceptual understanding (system knowledge), and strategic activity. Poor troubleshooters generate more incorrect hypotheses and pursue incorrect hypotheses longer than good troubleshooters; they are less likely to recognize critical information; they make fewer useful tests and more useless tests; they are ineffective in generating hypothesis; and they are poor in executing and verifying the results of their work (Morris & Rouse, 1985). These weaknesses result from poor conceptual understanding of the system they are troubleshooting and from a lack of integration among hypothesis generation, information gathering (testing), and thinking about the problem. Therefore, the TLE integrates these components to help learners to construct conceptual understanding and strategic knowledge through practice. The multilayered conceptual model provides the conceptual framework for the troubleshooter, in which learners must integrate information with hypotheses and strategies in order to proceed.

A potential difficulty with the TLE architecture is the responsibility that it places on learners. Learning with the TLE should require a fairly steep learning curve in the initial stages of learning. Learning to transfer troubleshooting skills really depends on invested mental effort (De Croock et al., 1998). This is the transfer paradox: Instructional strategies that lead to better transfer require learners to work harder or longer before initial performance is acquired. How many cases must be troubleshot before the learning curve begins to level out depends on the complexity of the system and the causal, analytical capacities of the learner.

5

STRATEGIC-PERFORMANCE PROBLEMS

WHAT ARE STRATEGIC-PERFORMANCE PROBLEMS?

In Chapter 3, I described different methods for making decisions. Decisions are ubiquitous. We make numerous decisions every day. The more important the decision, the more time we typically invest in considering alternatives, constructing scenarios and stories, and matching decision options to those scenarios (see Chapter 3 for descriptions of these activities). Such decisions are made in leisure time, when the decision maker spends as much time as necessary contemplating the options. However, there are more complex, dynamic decisions that frequently must be made by experienced practitioners under conditions of time-induced stress. Such problems include:

- military commanders leading troops in battle while under fire;
- arbitrator or mediator conducting negotiations among litigants;
- fire commanders leading fire fighters in extinguishing a large fire;
- intensive-care nurses treating neonatal patients;
- teacher dealing with a class of forty middle-school students;
- air-traffic controller guiding aircraft at a New York airport;
- quarterbacking during a football game;
- fighter pilot engaged in combat;
- executive director running a large conference;
- hostage negotiator during a large bank robbery;
- union negotiator during contract talks;
- senators trying to get a Bill to the floor;

- emergency-room doctors and nurses treating emergency patients.

The problems solved by these people require far more than decision making. They:

- are ill structured;
- occur in dynamic, uncertain, and changing environments;
- have shifting, ill defined, or competing goals;
- result in action–feedback loops (not simple, one-shot decisions);
- exist under times of stress;
- have high-stakes consequences (often life and death);
- have multiple players involved;
- are mediated by strategic organizational goals and norms.

(Orasanu & Connelly, 1993)

These are examples of strategic-performance problems, which are real-time, complex activities where the performers apply a complex and ill-structured strategy while maintaining situational awareness (Jonassen, 2000c). In order to achieve the strategic objective, the performer applies a complex set of tactical activities, usually under some time pressure. Typically there are a finite number of tactical activities that are used to accomplish the strategy; however, the mark of an expert tactical performer is his or her ability to improvise or construct and mentally rehearse new tactics to meet the strategy while maintaining situational awareness. In battlefield situations, superior officers identify a strategy. However, it is left to the inferior officer guiding men into battle to shift tactics on the fly in order to meet the strategic objective. Strategic-performance problems can be quite complex.

What I have referred to as strategic-performance problems (Jonassen, 2000c) have been extensively researched and reported by Gary Klein and his associates under the terms: naturalistic decision making (Crandall, Klein, & Hoffman, 2006; Klein, 1998; Klein, Orasanu, Calderwood, & Zsambok, 1993; Zsambok & Klein, 1997) and "tactical decision making under stress" (TADMUS). These are the kinds of problems that cannot be solved by novices. Rather, they rely on a certain level of experience.

HOW DO PEOPLE SOLVE STRATEGIC-PERFORMANCE PROBLEMS?

There are no models or empirically researched approaches to solving strategic-performance problems, per se. However, the research that Klein and his associates have conducted on naturalistic decision making provides very relevant advice for how to solve such problems.

Although they refer to these problems as decision making, the cognitive processes that problem solvers undergo in high-stress situations greatly exceeds traditional notions of decision making. These are the kinds of problems in which multiple decisions must be made under times of stress while maintaining situational awareness.

Klein (1998) distinguishes between traditional decision making and naturalistic decision making. Unlike traditional decision making (described in Chapter 3) that emphasizes deductive logical thinking, analysis of probabilities, and statistical analysis of decision options, decision making in naturalistic settings involves intuition (sizing up a situation quickly), mental simulations (imagining how a course of action may be carried out), metaphor (drawing on our prior experience), and storytelling (consolidating experiences and communicating them to others). Klein and his associates have studied numerous expert problem solvers, such as neonatal nurses, fireground commanders, and military commanders, all operating under time pressure in uncertain, dynamic, high-stakes situations where goals are unclear and there exist poorly defined procedures. Rather than weighing decision options serially, strategic performers may examine two or more options simultaneously, a process known as comparative evaluation. And unlike traditional decision making which seeks the optimal solution option, the goal of strategic performers is satisficing (Simon, 1957), that is, identifying an adequate solution rather than working toward an optimal solution. Simon believed that humans lacked the cognitive capacity to calculate and deductively compare the probabilities of all options. Needless to say, these are the kinds of problems that are not left to novices.

As described before, strategic-performance problems occur in dynamic, uncertain, and changing environments making these problems more ill structured than others. As indicated in Chapter 1, one important characteristic of problems is dynamicity, how much the conditions under which the problem is solved change and how rapidly they change. Strategic-performance problems are dynamic, where conditions change rapidly. While determining a solution to a military problem, the conditions of the problem can change dramatically as well, because the enemy is not standing still. Rather, they are attempting to adjust to the dynamics of the battlefield also. Because the battlefield conditions change dramatically, the goals of the problem also change frequently. What began as an offensive operation may quickly become defensive if your troops are outmaneuvered by the enemy. Likewise, there may be competing goals that call on more than one solution at a time. Another important condition of strategic-performance problems is the common time stress. These are real-time problems that require immediate solutions, where many problems are solved in leisure time, affording an unstressed amount of time to more extensively consider several possible solutions. Frequently, strategic-performance problems involve high-stakes consequences, requiring life-and-death decisions and actions. A pilot operating under emergency procedures must make decisions and take action immediately to save the lives of the passengers aboard the plane that he or she is flying. Unfortunately, the recent history of airline crashes has indicated that pilots frequently do not, in part because they were trained algorithmically. Others, however, have developed strategic problem-solving skills through experience. In late 2009, an airline pilot safely landed his plane, which had lost both engines on takeoff, in the Hudson River. He examined a few options and quickly decided on ditching because his mental simulation of that solution suggested that it provided the best chance for survival.

The process by which strategic problem solvers derive the best solution under time pressure in dynamic conditions with ill-defined goals is known as recognition primed decision making (RPDM) (Klein, 1993, 1997, 1998). Based on their previous experiences, expert problem solvers typically do not consider alternative options. Rather, their experience lets them see any situation (even non-routine ones) as examples of a prototype they have seen before so they know what action to take immediately. Those prior experiences are often referred to as event schemas or scripts (Schank & Abelson, 1977). In diagnostic medicine, they are known as illness scripts. Rather than performing a routine based on diagnostic logic, expert physicians recognize patterns of symptoms and fire illness scripts when diagnosing patients. Based on hundreds or thousands of experiences, problem solvers recognize key patterns that indicate the dynamics of a situation. Those schemas or scripts enable problem solvers to immediately size up a situation and automatically fire solutions. Sometimes this process is more automatic than others. That is, the level of automaticity depends on how recognizable the problem is, so there are three variations to recognition-primed decision making (see Figure 5.1).

Expert performance in problem solving is based on recollection of experiences, where each experience is indexed in terms of cues, expectancies, goals, and typical actions. RPDM is basically a process of recognizing similar experiences and using the lessons learned from those experiences to solve a new problem (a process known as case-based reasoning; see Chapter 12 for an extended description). That is, when intensive-care-unit (ICU) nurses manage critically ill patients, they look for common cues (skin color, temperature, behavior, etc.).

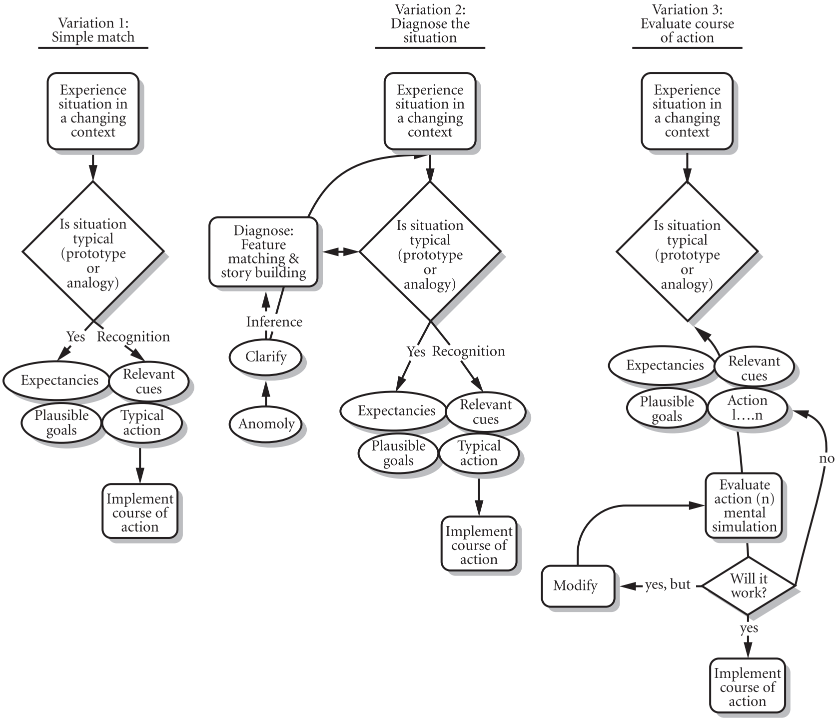


Figure 5.1 Forms of recognition-primed decision making.

Those cues help them to diagnose any emergent problems with the patient, and, based on those cues, the nurse generates expectancies about how the patient will progress and what actions to take in order to maintain stability in the patient. The goals of ICU nurses varies from normal ward nurses because of the severity of the problems of patients in ICU. Given any new situation (fire, battle, patient presentation, student behavior), the strategic-performance problem solver will engage in pattern matching, by recognizing cues and features of the situation and matching them to previous experiences. The simplest and easiest form of RPDM is illustrated as Variation 1 in Figure 5.1. The problem solver recognizes the situation as typical and familiar, understands what goals make sense, which cues are important, what to expect next, and typical ways of responding and recognizing course of action that is likely to succeed (Ross, Lussier, & Klein, 2005).

In Variation 2, the new situation is somewhat atypical, so the problem solver is required to diagnose the situation. The problem solver will not know that until some part of the solution is attempted and he or she realizes that his or her expectations have been violated. That recognition is probably only possible with highly skilled or expert performers. That is, applying a common event schema will not work, so the problem solver usually gathers more information in order to make the diagnosis. The problem solver must identify the features in order to construct a story about the situation. The problem solver will try to match that story to a previously encountered story or experience. Frequently, problem solvers will consult a colleague who may recognize the pattern of cues based on a previous experience and attempt to apply that story. Once the previous story is used as the prototype for comparing with the new situation to, the solution process becomes fairly routine.

In Variation 3, no schema exists for applying to the new situations. That is, the pattern of cues and expectancies in the new situation does not match existing schemas, so the problem solver must conduct a mental simulation. A mental simulation is "the ability to imagine people and objects consciously and to transform those people and objects through several transitions, finally picturing them in a different way than at the start" (Klein, 1998, p. 45). A mental simulation is a scenario (see scenario construction in Chapters 3 and 6) that is constructed on the fly by the problem solver about the consequences of various actions. Problem solvers usually consider these one at a time. They will construct a mental simulation about a course of action and decide if the course of action should be applied based on the mentally simulated results. If the mental simulation predicts failure, the problem solver may attempt to construct and consider a new simulation. Note the difference between this focused mental simulation and hypothesis generation engaged by troubleshooting.

RPDM can only occur in experienced practitioners. In order to recognize problem types, the problem solver needs to have experienced a wide range of similar problems. This requirement is what makes solving strategic-performance problems difficult to train. As described later, novices may benefit from exposure to multiple case examples of problems. Clearly, that is a requirement for this kind of problem solving. Although it appears similar to troubleshooting, in RPDM the goal is undefined, may involve satisficing, and is usually performed under time stress with more incomplete or uncertain information.

HOW DO WE ANALYZE STRATEGIC-PERFORMANCE PROBLEMS?

The primary methodology for analyzing complex, time-pressured tasks that characterize strategic-performance problems is a cognitive task analysis method known as the critical-decision method (CDM). CDM is a multiple-pass event retrospection about a specific high-stress event that is structured and guided by probe questions (Crandall et al., 2006; Hoffman, Crandall, & Shadbolt, 1998). Experienced practitioners provide an account of such an experience that is followed by three information-gathering sweeps back through experience in order to verify the timeline and to identify different decision points (times when courses of action were required).

CDM interviews are organized around an initial, unstructured account of a specific incident, such as a fire, a battle, a patient, a game, or a negotiation). The incident account is generated by the interviewee in response to a specific open-ended question posed by the interviewers, and it provides the structure for the interview that follows. For example, in a study of ICU nurses' clinical judgments (Crandall & Getchell-Reiter, 1993), each nurse was asked to select an incident in which her patient-assessment skills had made a difference to the patient's outcome. In studies of fireground command decision making, participants were asked to recall an incident in which their expertise as a fireground commander was particularly challenged (Klein, Calderwood, & Clinton-Cirocco, 1986; Calderwood, Crandall, & Klein, 1987). Once the practitioner identifies a relevant incident, he or she recounts the episode in its entirety, with no interruptions from the interviewer. The interviewer serves the role of an active listener at this point. The respondent's account, solicited in this non-interfering way, provides the focus and structure of the remainder of the interview. By requesting personal accounts of a certain type of event, and by structuring the interview around that account, potential interviewer biases are minimized. Once the report of the incident has been completed, the CDM interviewer leads the participant back over his or her incident account several times, using probes designed to focus attention on particular aspects of the incident and to solicit information about them. CDM probes are designed to elicit specific detailed descriptions about the event, with particular emphasis on perceptual aspects (e.g., what was actually seen, heard, considered, remembered) instead of asking people for their general impressions or for explanations or rationalizations about why they had made a particular decision. The probes are designed to progressively deepen understanding of the interviewee's account.

The basic mechanism of making strategic-performance problems is situation assessment. This is the process by which a practitioner quickly analyzes any situation for cues, expectations, and possible decisions. For example, Table 5.1 illustrates the kind of situation assessment that a quarterback must make in less than three seconds.

Table 5.1
Situation assessment of NFL play execution by quarterback

Goal: Complete forward pass for maximum yardage gain; avoid sack.

Cues: Read defense at line of scrimmage; defensive backs in man-to-man coverage; linebackers signal blitz.

Decision point 1: Which receiver will most likely be open?

Expectation: Tight end on slant over middle.

Decision point 2: Call audible to tight end to look for pass and right tackle to block out middle linebacker.

Cues: Ball is snapped; quarterback drops back in pocket and looks downfield; linemen and outside linebackers rush toward quarterback.

Expectation: Knows defense expecting pass, plan to blitz.

Cues: Tight end held at like of scrimmage.

Expectation: Tight end unlikely to get open.

Decision point 3: Status of secondary receiver on post pattern; possible target.

Cues: Secondary receiver covered.

Expectation: Probable interception.

Decision point 4: Throw to third receiver, tailback on screen to right?

Cues: Left cornerback playing back.

Expectation: Probable completion.

Decision point 5: Throw pass to tailback.

The information obtained via CDM is concrete and specific, reflects the point of view of the decision maker, and is grounded in actual incidents. For these reasons, the methods have been found to provide an excellent basis for development of instructional materials and programs, the design of decision-support systems, and the development of human–computer interfaces.

HOW DO YOU CONDUCT THE CRITICAL DECISION METHOD?

The steps that are normally completed in a critical decision analysis include:

1. eliciting an incident;
2. timeline verification and decision point identification;
3. progressive deepening and the story behind the story
4. “what if?” expert–novice differences, decision errors and more.

1. Eliciting an Incident

A critical part of the CDM interview is eliciting an incident. In accord with the goals of the project, interviewers will have decided ahead of time on an opening query. The query points the expert toward certain types of events and sparks recall in accord with that memory search. The opening query typically poses a type of event and asks for an example where the expert's decision making altered the outcome or where things would have turned out differently if he or she had not been there to intervene. The idea is to help the subject-matter expert identify cases that are non-routine, especially challenging, or difficult—cases where one might expect differences between the decisions and actions of an expert and of someone with less experience.

Once the participant identifies a relevant incident, he or she is asked to briefly recount the episode. Typically, the initial account is elicited by asking the participant to "walk us through" the incident and to recount it in its entirety. The interviewer acts as an active listener, asking few if any questions, and allowing the participant to structure the incident account himself or herself. The participant's account, solicited in this non-interfering way, provides a framework and structure that the interviewer will use throughout the remainder of the interview. By requesting personal accounts of a specific event and by organizing the interview around that account, potential interviewer biases are minimized.

Once the expert has completed his or her initial recounting of the incident, the interviewer retells the story. The participant is asked to attend to the details and sequence and to correct any errors or gaps in the interviewer's record of the incident. The interviewer presents the incident account back to the participant, matching as closely as possible the expert's own phrasing and terminology, as well as incident content and sequence. Participants often offer corrections and additional, clarifying details. This critical step allows interviewers and participants to arrive at a shared view of the incident.

2. Timeline Verification and Decision Point Identification

In this phase of the interview, the expert goes back over the incident account a second time, seeking to structure and organize the account into ordered segments. The purpose of this phase is to allow the elicitor to construct a timeline. The expert is asked for approximate times of key events and turning points within the incident. The timeline is composed along a domain-meaningful temporal scale, based on the elicitor's judgment about the important events, the important decisions, and the important actions taken. The timeline is shared with and verified by the expert as it is being constructed and often becomes a common point of reference throughout the remainder of the interview.

The elicitor's goal is to capture the salient events within the incident, ordered by time and expressed in terms of the points where important input information was received or acquired, points where decisions were made, and points where actions were taken. These "decision points" represent critical junctures within the event—points where there existed different possible ways to understanding a situation or different possible actions available.

At the conclusion of the second sweep through the incident account, the elicitor has produced a verified, refined documentation of events. The sweep accomplishes in a systematic way what is ordinarily accomplished by less systematic interview procedures that ask, for example, "What do you do at each step in this procedure?" and "When would you do that?" The CDM anchors the knowledge-elicitation process in the recall of a specific incident rather than by treating knowledge in terms of general or abstracted procedures.

3. Progressive Deepening and the Story behind the Story

During the third sweep through the incident, the CDM interviewer leads the participant back over each segment of the incident account identified in Sweep 2, employing probing questions (see Table 5.2) designed to focus attention on particular aspects of the incident and to

Table 5.2
CDM question probes used during CDM

Probe Type	Probe Content
Cues	What were you hearing, seeing, smelling?
Knowledge	What information did you use on making this decision and how was it obtained?
Analogues	Were you reminded of a previous experience?
Goals	What were your specific goals and objectives at the time?
Options	What other courses of action were considered or possible?
Mental modeling	Did you imagine the possible consequences of this action? Did you imagine how events would unfold?
Decision making	How much time pressure was in making this decision? How long did it take you to make this decision?
Errors	What mistakes are likely at this point?
Hypotheticals	If a key feature of the situation had been different, how would it have affected your decision?

solicit information about them. The probes are designed to progressively deepen understanding of the event to build a comprehensive, detailed, and context-specific account of the incident from the perspective of the decision maker.

Solicited information depends on the purpose of the study but might include presence or absence of salient cues and the nature of those cues, assessment of the situation and the basis of that assessment, expectations about how the situation might have evolved, goals considered, and options evaluated and chosen. Because information is elicited specific to a particular decision and incident, the context in which the decision maker is operating remains intact and becomes part of the data record.

In this phase of the interview, there is often a sense of the participant reliving the incident, and reporting on it as it unfolds. The interviewer focuses the participant's attention on the array of cues and information available within the situation, eliciting the meanings those cues hold and the expectancies, goals, and actions they engender. Out of this exploration comes a version of the incident rich in perceptual cues and details of judgment and decision making that are rarely captured in traditional verbal protocol methods. It is the story behind the initial account of the incident and the phase of the interview where the participants expertise, knowledge and skill played out against the background of a specific event are revealed.

4. *"What If?" Expert–Novice Differences, Decision Errors and More*

The final sweep through the incident provides an opportunity for interviewers to shift perspective, moving away from the participants' actual, lived experience of the event to a more external view. During this phase, interviewers often use a "what if" strategy. They pose various changes to the incident account and ask the participant to speculate on what would have happened differently. In studies of expert decision making, for example, the query might be, "At this point in the incident, what if it had been a novice present, rather than someone with your level of proficiency. Would they have noticed Y? Would they have known to do X?" Answers to such questions can provide important insights into domain-specific expertise. Or, one might go back over each decision point and ask the expert to identify potential errors and how and why those errors might occur, in order to better understand the vulnerabilities and critical junctures within the incident. This final sweep is a kind of risk assessment. In RPDM, the costs of alternate actions and consequences of error are considered and form one basis of the optimization (or satisficing).

WHAT ARE THE COMPONENTS OF A STRATEGIC-PERFORMANCE-PROBLEM LEARNING ENVIRONMENT?

Expert decision making is unconscious and requires a rich store of experiences, so how do we teach something that is unconscious (Ross et al., 2005)? Therefore, training people to perform strategic-performance problems can be very difficult. It is questionable how effective any training may be for novices, as naturalistic decision making has always been conducted with skilled practitioners and experts. There is almost no empirical research or evidence with novices, so preparing novices to solve strategic-performance problems should be pursued very carefully. The primary goal of any such training, for novices or experienced practitioners, should focus on situation assessment and response to that situation. Therefore, the primary method will be exposing trainees to assess situations in a simulation, at first slowly but gradually accelerating the pace of training to required situation assessment in short periods of time and with increasing "noise" and uncertainty in the environment. These are not the usual kind of simulation, because it varies level of abstraction/realism, and it includes dialog/reflection activities.

HOW CAN SIMULATIONS BE USED IN STRATEGIC-PERFORMANCE PROBLEMS?

The heart of strategic-performance-problem-solving environments is the simulation. Learning to solve strategic-performance problems using recognition primed decision making involves the processes of situation assessment (recognizing patterns in situations) which requires making fine perceptual discriminations in order to recognize patterns of relevant cues, goals, and expectations (Cohen, Freeman, & Thompson, 1998; Klein, 1997). The simulation enables learners to perform those tasks.

Figure 5.2 provides a model for training recognition primed decision making. The basis for learning to assess situations is a large collection of strategic-performance cases in a simulation. For each of those practice cases, the goal is to help students to learn how to recognize relevant cues, goals, and expectations. That requires practice, practice, and more practice. Cases as examples may be presented as text displays, stories, or even videos if the important cues and information are visual. For each case as example, the objective for students is to identify the relevant cues, to classify the kind of problem it is (what is the goal to be accomplished), and to determine expectations about what will happen

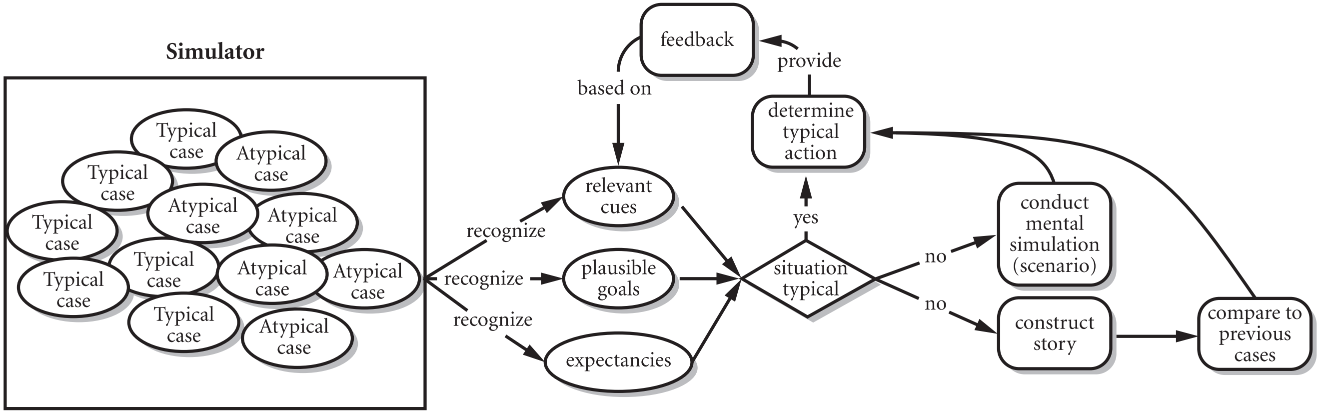


Figure 5.2 Instructional model for strategic performance problems.

next. Recognizing anomalies and typicality (identifying cues, patterns and strategies) can be complex. Various scaffolds can be added to these examples at the beginning of practice and faded throughout the practice sequence. Here are some suggestions:

- The purpose of initial cases will be concept generalization, that is, enabling students to induce their schema for a situation based on a set of common characteristics. So, in the initial practice cases, present only one or two relevant cues or items that students need to learn at a time. Add cues and pieces of information gradually, one at a time until all important cues are present in the example.
- Signal the cues and informative elements. That is, help students to recognize the salient cues in the information display. Salomon (1979) provides a book full of suggested mechanisms for cue-important information to improve cue salience. In one of his most famous studies, he continuously zoomed in and out on important elements in the visual display. Learners were able to transfer the skill when the zooming was removed.
- After the nature of any situation is learned through case-based practice, add anomalous cues, events, or expectations. Students need to learn to discriminate between typical situations and atypical situations. That is primarily a matter of determining if the cues are normal and whether the goals and expectations of the situation are met. Initial examples may signal the atypical cues to help learners to discriminate typical vs. atypical cues. Now comes the difficult part. Once students are able to assess a situation, it is necessary to teach them to determine appropriate action. However, the action to be taken depends on the typicality of the case and the situation assessment. If the case is typical, then the student needs to be prompted for the appropriate action and provided analytical feedback based on the relevant cues, goals.
- After considerable practice, provide only the beginning of the example and require the students to construct a story indicating how they believe that the situation will unfold. Story construction will test the students' understanding of how different situations develop. The story requires students to reason causally (see Chapter 17), an essential part of any kind of problem solving.
- For each situation assessment, the student should describe the actions that should be taken to address the situation. For each recommended action, feedback to the students is essential, pointing out why the action will or will not rectify the situation.

- If the student recognizes the case as atypical they may construct a scenario (see Chapter 3 or 6) or mental simulation describing how they believe that the situation will unfold. If there exists in the students' memory an action or set of actions that will address the situation, they may suggest that and receive feedback about the viability of their solution.
- If the student recognizes the situation as atypical and is unaware of an existing solution, they need to be prompted to think of alternative solutions and construct mental simulations about how they believe that each of those alternative solutions will work. Analytical feedback is needed for each of these alternative solutions.
- Following each training session, students should engage in reflection on action (Schön, 1983) or a retrospective analysis of their assessments, solution decisions, and the processes they went through to make decisions and take action. This process relative to naturalistic decision making has been recently described as macrocogniton (Schraagen, Militello, Ormerod, & Lipshitz, 2008).

How many practice cases are needed depends on the complexity of the identification task, the number of plausible alternative solutions, the nature of the learners, and the manner in which the cases are presented. For purposes of providing such training, it will be necessary to compile a large experience bank. Learning those cues, patterns and solution strategies can be very time consuming, because they need to be over-learned (to approach automaticity) so only a finite set of cues, patterns and strategies can be learned in a given period of time.

6

POLICY-ANALYSIS PROBLEMS

WHAT ARE POLICY-ANALYSIS PROBLEMS?

Pick up any newspaper, and the pages will be filed with local, regional, national, and international policy-analysis problems. Local governments and agencies address such problems as:

- How do we provide affordable housing for people living near the poverty line?
- Should the city build a new high school and, if so, where, and with what facilities?
- How do we make up for lagging sales tax revenues in order to fund existing programs?
- Should we regulate housing permits and construction quality more closely?

Most problems solved by state governments and agencies address policy issues, such as:

- How do we stimulate greater job growth?
- How do we entice more companies to establish facilities in our state?
- How do we maintain or highways and crumbling bridges?
- What environmental standards should be imposed on manufacturing companies?
- Should we establish term limits for state legislators?
- What graduation requirements should be imposed on state high schools?

- How do we reduce the incidence of real-estate investment scams in our state?
- Do we provide sufficient services to children with emotional and behavioral difficulties?
- How do we address increasing levels of school violence?
- How do we address gaps in Medicare funding?

Most problems solved by national governments and agencies constantly address policy issues, such as:

- How should we deal with emerging rogue nations such as North Korea?
- How do we provide affordable heath care to the uninsured?
- How do we prepare for a flu pandemic?
- How do we pay for crumbling infrastructure in our country?
- Should we build a new high-speed train system?
- What is the fairest taxation policy?
- How do we stimulate the economy without creating high levels of inflation?

Policy problems tend to be complex, ill-structured decision-making problems that normally are not time pressured. What makes policy problems so complex and ill structured? Policy problems usually involve a host of city planners, policy analysts, community managers, local, state, and national legislators, citizens, agency leaders, and many other stakeholders, most of whom assume fundamentally different positions that are supported by very different values and beliefs. So these different stakeholders are usually seeking different outcomes that cannot be equated. For example, a small western mountain town is currently trying to decide to limit permits to hunt elk in the area. The state Department of Wildlife is tasked with determining the policy, so they are soliciting information from interested parties. Their obvious role is to protect wildlife. However, other parties, such as the local cattle-breeders association, want elk herds thinned out because the elk are competing with the ranchers for grazing opportunities. The local retailers want no restrictions so more hunters will come into the community in the fall to hunt and spend money while in the community. The conservationists seek to protect the elk herds, because it is the right thing to do. And then there is the weather. The previous season, record cold temperatures and snowfall depleted a significant number of the elk herd. These various groups, like most groups, seek to further their own interests. However, there is no way to equate those interests. Although the bulk of policy problems have economic implications, there usually exist political, social, environmental, psychological, emotional, historical, and other important perspectives that are relevant to policy problems.

HOW ARE POLICY PROBLEMS SOLVED?

Numerous models for solving policy problems have been published. These various models are conceptually coherent, differing somewhat in terms of specific steps. Among the better known models, Patton and Sawicki (1986) claim that solving policy problems requires the following six steps:

1. **Verify, define, and detail the problem.** This process involves clarifying what different parties regard as the nature of the problem, because the objectives of different parties often vary considerably.
2. **Establish evaluation criteria.** Just as objectives vary, the criteria for evaluating the success of any solution will also vary. So, in order to compare alternatives, relevant evaluation criteria must be established. Criteria may include cost, effectiveness, acceptable risk, efficiency, equity, administrative ease, legality, and political acceptability. Needless to say, different parties will favor different criteria as they benefit more from some criteria than others.
3. **Identify alternative policies.** Because of the multiple objectives established in the first step, generating alternative policies can be tricky. However, the possible solutions will likely emerge from those objectives. After some solutions have been identified, combining or compromising some solutions may generate the best solution.
4. **Evaluate alternative policies.** In order to evaluate different policies, it is necessary to evaluate how each possible alternative benefits the criteria previously established. Additional data may be needed in order to analyze those benefits, such as additional economic benefits, social implications, and so on. It is necessary to analyze each alternative using a variety of quantitative and qualitative means.
5. **Display and distinguish among alternative policies.** The results of the previous step explain the degree to which criteria are met in each of the alternatives. This may require the use of decision matrices or the construction of scenarios described in Chapter 3. Scenario construction will be explained later in this chapter.

6. **Monitoring the implemented policy.** Once a policy has been implemented, it is important to monitor the effects of that policy and to determine the impact of the policy. Based on this evaluation, the policy may need to be rejected, modified, or at least reconsidered.

Another commonly referenced process for solving policy problems was provided by Bardach (2000):

1. **Define the problem.** Be clear about the nature of the problem (e.g., breakdown of system, low living standards, discrimination against minorities, failure of government to function). Don't define the problem as a solution (e.g., new schools are being built too slowly).
2. **Assemble evidence.** In order to assess the nature and extent of the problem you are trying to define, you may want to assess policies that others have used.
3. **Construct the alternatives.** The alternatives may be modeled (described later in this chapter and also in Chapter 13), focusing on the causal relationships (see Chapter 17) and the incentives and constraints at work in the problem context.
4. **Select and apply criteria.** Apply evaluative criteria to alternative solutions (e.g., efficiency, equality, fairness, freedom, community needs, legality, acceptability).
5. **Project the outcomes.** Make predictions about the possible outcomes by constructing scenarios (described in Chapter 3 and later in this chapter).
6. **Confront the trade-offs.** Use a decision matrix to compare and contrast alternatives (see Chapter 3 for a description of decision matrices).
7. **Make the decision.**
8. **Tell your story.** Communicate your decisions and the rationale for the decision that you made.

Numerous other models of policy analysis have been published and applied in a variety of situations. All of those models follow steps similar to the two examples just presented. Policy-problem-solving models all appear to be phase models that describe a series of steps or phases that are applied to all policy problems in much the same way.

Unlike strategic performance problems (see Chapter 5) where decisions are made under time pressure involving possible life-and-death decisions, policy problems are usually solved in without such time pressures. That is, policy decisions often stretch out for weeks, months, or even years. Why? Despite a lack of psychological research and theories on policy analysis, I hope to uncover some of the cognitive processes that underlie those phases and suggest a variety of cases and processes that constitute effective policy-problem-solving learning environments.

Policy problems ultimately require decisions to be made about which policy will be implemented or what the components of an acceptable policy will be. In nearly every policy problem, there are multiple voices and perspectives related to the policy decision. Therefore, most policy problems must be socially negotiated and co-constructed based on the inputs from numerous people. There rarely, if ever, is a single perspective that represents the best solution to any policy problem. Because of the stridence of opinions that are considered, compromise is often difficult. The decisions that accommodate the most perspectives will often result in the most desirable actions. Because of the social nature of the problem-solving process, policy problems can be quite difficult to represent and to solve.

Learning to solve policy problems requires that learners learn to accommodate the ambiguity implicit in any uncertain solution. Unfortunately, tolerance for ambiguity is low among teachers and learners. Why? It has to do with their epistemic beliefs (see also Chapter 1), that is, what we believe that knowledge, truth, and learning means. Research in epistemological beliefs shows that people develop their beliefs from simple, black-and-white thinking, through an exploration of multiple perspectives, to complex, relativistic thinking (Perry, 1970). The epistemological foundation for most education is what Baxter-Magolda (1987) calls absolute knowing, where individuals believe that knowledge and truth are certain and should be obtained from authorities. Solving policy problems requires transitional knowing (knowledge is partially certain and requires understanding using logic, debate, research), independent knowing (knowledge is uncertain and requires independent thinking and open-mindedness), and contextual knowing (knowledge is based on evidence in context). Because learners are most commonly absolute thinkers, they will find policy problems very challenging, because there is no correct answer. However, if learners never face ill-structured, policy problems, they will probably never develop independent or contextual thinking skills. So exposure to the ambiguity implicit in policy problems represents a productive, if difficult, learning experience.

WHAT ARE THE COMPONENTS OF A POLICY-PROBLEM LEARNING ENVIRONMENT?

Because policy-analysis problems are more ill structured and context dependent than other kinds of well-structured problems, it is necessary to develop a more authentic and situated task environment (Voss & Post, 1988). Policy-analysis thinking, to a substantial degree, is determined by the context in which it occurs, so it is important to understand the social, political, and organizational context surrounding the problem. Therefore, when designing policy-analysis learning environments, an analysis of the context in which that policy problem emerges needs to be conducted. In what context does this policy analysis occur? Is it familial, local, regional, national, or international? Who are the stakeholders? What are their positions? What principles, themes, or theories do those positions represent? What are the political, organizational, social, economic, and historical constraints imposed by the context? All of the important information will need to be represented in the establishing story and supported in the cases as alternative perspectives, both described later.

Figure 6.1 illustrates my model for designing policy-analysis learning environments. There is little if any psychological research on how policy analysis is best conducted, so my model is based on my analysis and some speculation. I next describe each of the components that such an environment may include.

HOW DO WE REPRESENT POLICY PROBLEMS?

Case-analysis problems are usually represented by stories (see Chapter 12 for a detailed rationale for using stories). Why? Stories are better understood, better remembered, and more empathic than didactic representations of problems. The following excerpt is taken from a policy-analysis learning environment that we developed on the sociology of welfare. This particular story introduces the problem in the welfare cycle (seeking assistance, support, welfare to work). The problem has to do with how to help people through the welfare-to-work cycle. Another major goal of the environment was to invoke empathic responses from culturally isolated students at a large state university.

> **Tuesday, February 2, 1999**
>
> My name's Tiffany. I'm on my way to Lewistown with my daughter, Stephanie. Stephanie's almost five now. I had her when I was eighteen. My home and friends are in Detroit. I can't stay there no more.

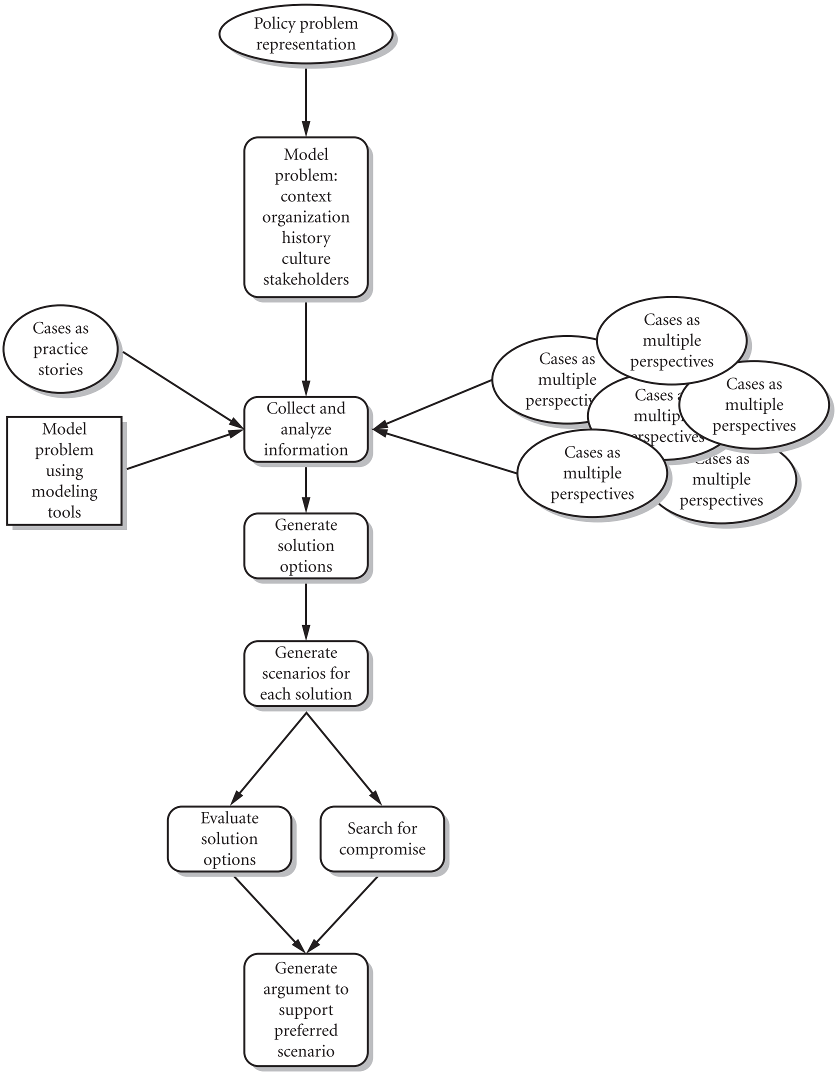


Figure 6.1 Model for case/system analysis problem-solving environment.

I got involved with a gang there, selling drugs and dealin'. It took me five years to realize that I didn't want to live like that no more. I was stealin' and doing things I never thought I would. I love my little girl. I realized I would be harmin' her if I stayed with them.

When you've done and seen what I have, there's no point in wanting "out" unless you're prepared to do it. So I'm leaving, with no cash, no help from no one. Just Steph and me. Yeah, this

> has been my "Happy Christmas." I'm lookin' for my natural mother. I know she lived in Lewiston, Pennsylvania, when I was born. Its a long shot, though. I have an address for her for 1992. I ain't never met her. She don't know I'm comin'. I have nowhere else to go—just can't stay in Detroit: no way. I'm near eight months knocked up. I gotta get help, right away when I get there, for the sake of my babies.
>
> **Wednesday, February 3, 1999 (5:30 P.M.)**
>
> Stephanie ain't never traveled on no greyhound bus before. A twenty-hour ride has just about dimmed her enthusiasm—poor baby. Thank God she slept. We left the Howard Street station in Detroit at 10:00 last night and got here at 5:15 today. In this rotten weather, it'll be dark soon. We haven't eaten since we finished our snacks. Jeez, the smell from this Market Street Grill is drivin' me crazy. What have I done? My ticket was $59. That's crazy! Maybe I should o' kept my money.
>
> I aint got no idea where to go here. The number I have for my mother ain't givin' me no answer. I only have three quarters for the phone. Thirty dollars and my kid and this ol' beach bag with Steph's clothes and beanie babies and some things for myself, that's all I have. And jeez, is this place small, and cold. I know I gotta find us some help. This number still ain't answering. There's no message. Maybe this isn't even the number . . . It's gettin' late. What are we gonna do?

Representing case-analysis problems in terms of stories is not enough to engage learners in the kind of thinking that is necessary for solving case problems. The story should be embellished with relevant legal statutes, welfare policies of the state, newspaper stories about similar cases, or interviews with family members, welfare agents, or others with relevant perspectives. A policy-analysis story includes multiple forms of representation necessary to tell the whole story.

When telling the story and setting the problem, it is equally, if not more, important to provide students with a specific, authentic task to solve. In the social-welfare problem just described, we required students to counsel this woman, who was seeking to move from welfare to work. Their counseling not only had to be legally correct (the students became very frustrated by the complexity of the forms and the procedures that had to be completed by the recipients) but also empathic. The task may also have focused on determining the benefits for which this woman is eligible. Needless to say, different tasks will focus the attention of students on different information elements that are needed to solve the problem.

The task also needs to be fairly specific. The task for a foreign-policy analysis problem on the Middle East might require the students to act as foreign-policy analysts for the State Department tasked with recommending specific policy actions to the Secretary of State about whether Palestinians should be granted independent statehood. That is, there should be a specific kind of outcome (advice) associated with the task: not just a report but a report with specific action items. The more purposeful the task, the more engaging it will be. The same environment may be repurposed by redefining the task. Rather than making recommendations about statehood for the Palestinians, the task might be redefined as "How do we prevent further expansion of Israeli settlements into disputed lands?" Except for the task, the remainder of the environment may be the same or very similar.

HOW DO WE COLLECT AND ANALYZE INFORMATION ABOUT THE POLICY?

Most policy problems are replete with different perspectives on what the problem is, what issues are most relevant to the problem, and how the problem should be solved. The front page of any newspaper normally includes descriptions of policy problems. According to the model in Figure 6.1, after setting the problem students must begin collecting and analyzing different interpretations and perspectives on the problem.

WHICH KINDS OF MULTIPLE PERSPECTIVES DO WE PRESENT FOR POLICY-ANALYSIS PROBLEMS?

Based on the contextual analysis for each problem, you need to represent all of the important perspectives on that problem by presenting cases as alternative perspectives (see Chapter 13). As described in Chapter 13, each case (in this case minimal representations or examples of different viewpoints) that represent a meaningful interpretation of the problem or some aspect of the problem. Based on cognitive flexibility theory (Spiro, Feltovich, Jacobson, & Coulson, 1991), by examining the different facets of a problem, students are better able to construct a rich and robust mental representation of the problem. Depending on the problem, different kinds of perspectives may be represented.

The most obvious kind of case perspective to provide are personal perspectives. In a policy-problem learning environment that we developed years ago, one problem focused on the liberation of Kosovo from the Serbs. This was a complex, international policy problem that was vexing the Clinton Administration. Several solutions were being considered, including declaring Kosovo an interim international protectorate, establishing Kosovo as an independent state, negotiating with Serbia conditions for the partition of Kosovo with some parts to fall under Kosovar Albanian rule, and some parts under Yugoslavian rule, or making Kosovo part of a greater Albania. In order to make such a policy decision, Clinton relied on numerous advisers in his cabinet and called on each to provide their perspective. In the environment, we represented the perspectives that were taken or would be taken by different members of the committee listed on the left side of Figure 6.2, which also illustrates the perspective of the Chairman of the Senate Foreign Relations Committee. Needless to say, the perspectives of the different members of the committee varied substantially.

A problem as complex as the Kosovo crisis, or any other international crisis for that matter, can and should be viewed through different disciplinary lenses. Cases or examples that represent these different disciplinary perspectives may also be presented. For an international crisis, there are clearly historical, anthropological, sociological, legal, economic, psychological, religious, and geographical perspectives that need to be considered. Historically, it is important to describe the war in 1389 when the Kosovars defeated the Serbs, who never forgot. Anthropologically and sociologically, the Kosovars and Serbs have different beliefs and values that emerged throughout history, as did the Macedonians, Croatians, and other societies in the Balkans. Kosovars and Serbs have different religious values, so cases showing the

Interagency Committee :	Representatives from the Senate Committee on Foreign Relations
Dept/ or Agency of US Government :	House & Senate
Perspectives Represented :	Public Opinion-Congress and Senate

The chairman on the Senate Foreign Relations commitee, Helms

As you all know the house there has been fierce debate in the House and Senate over why the administration didn't seek congressional and senate approval for the action in Kosovo prior to the ground war. This was illustrated quite effectively in the debate over **S.J.RES.11** introduced by Sen Smith, Bob which was the a joint resolution prohibiting the use of funds for military operations in the Federal Republic of Yugoslavia (Serbia and Montenegro) unless Congress enacts specific authorization in law for the conduct of those operations. However This resolution was narrowly defeated through heavy political lobbying by the President's chief of staff and his advisors. A more pertinent resolution, H. J. Res. 44, introduced by Rep. Tom Campbell which initiated a declaration of war on Yugoslav was also shot down because the committee believed that, if adopted, H.J. Res. 44 would have adverse repercussions within the North Atlantic Alliance. It would place the United States alone in a declared state of war with the FRY. It would compound strains in U.S. relations with Russia, and could strengthen Mr. Milosevic politically within the FRY. A declaration of war would also blur the message that our allies and we have been trying to convey to the Serbian people regarding the limited objectives of Operation Allied Force. So the introduction of ground troops and the taking of the region was accomplished, as we all know without a congressional declaration of war. A fact, which doesn't sit well with many congressman and senators, even though there is historical precedent for this. Coupled with this was the passage by a narrow margin of the SERBIA DEMOCRATIZATION ACT OF 1999 *S. 720*. A bill to promote the development of a government in the Federal Republic of Yugoslavia (Serbia and Montenegro) based on democratic principles and the rule of law.

We are now faced with the task of identifying which option the Senate and Congress will endorse. Right now the house Committee on Foreign Relations and the Senate Committee on Kosovo would push strongly for options 1, or 2 with very little partitioning of Kosovo in order to send a clear message to Milosovic and future Ethnic cleansers. Partitioning of much of Kosovo would be viewed by these committees as a compromise and an insult to the dead veterans which fought so hard to secure the entire region.

Figure 6.2 Committee member perspective on Kosovo crisis.

importance of Islam to the Kosovars and Christianity to the Serbs would provide different perspectives on the problem. Many wars have been waged in the name of religion. The mountainous geography of the eastern shores of the Adriatic also played a role in the Kosovo crisis. Psychologically, the Serbs have been a fiercely proud and hegemonistic people, where Kosovo was populated with poor ethnic Albanians. All of these perspectives shed different light on the problem. It is critical to represent diverse perspectives. A common criticism of many administrations is that they start with an ideologically driven decision and work backward to build a story to justify it, ignoring disconfirming evidence and other perspectives and even inventing information as convenient. Your perspectives may include these but hopefully will provide a more balanced set of perspectives.

As recommended by cognitive flexibility theory (Spiro et al., 1991; Chapter 13), another kind of perspective is thematic. That is, problems may be analyzed using different themes that emerge from the problem or the personal perspectives described before. That is, different people have different perspectives that represent different themes. Themes that could be used to analyze the Kosovo crisis may include freedom vs. external control, unity vs. fragmentation, or consensus vs. power. These themes can be represented as examples of how each theme had played out in other experiences or how they might be used to contrast solutions to the policy problem being examined. Cases are examples that represent each of these thematic perspectives will provide meaningful perspectives on the problem.

As illustrated in Figure 6.1, other perspectives may be included by providing cases as prior experiences. Described in greater detail in Chapter 12, presenting cases that represent prior experiences is supported by case-based reasoning (Kolodner, 1993). Cases as prior experiences represent stories of similar experiences from which practitioners may gain meaningful interpretations or solutions to problems. For resolving the Kosovo crisis, stories about conflicts in the Czech Republic, Northern Ireland, Sudan, Liberia, and Turkey are based on experiences that are similar to the Kosovo crisis. For example, in Northern Ireland, religious differences fueled the conflict between the Catholics and the Protestants. Comparing the Kosovo crisis to cases describing religious differences in Northern Ireland provides important perspectives on the problem.

I have briefly described how mini-cases that represent different kinds of perspectives can be added to policy-problem learning environments. Each case should provide a relevant interpretation of the problem. Learners must then construct their own mental models of the problem in order to generate and support appropriate solutions. In order to help learners to construct mental models, I recommend that learners construct computer-based models of the problem. These models externalize learners' mental models enabling them to articulate and refine their mental models (Jonassen, 2006a).

HOW CAN LEARNERS MODEL POLICY PROBLEMS?

While collecting and analyzing information and perspectives on the problem, it will be very productive for the learners to construct models of the problem in order to better understand the relationships among the problem elements. The variety of computer-based tools that can be used to model problems is more completely described in Chapter 19. Why should students construct models of the problems they are trying to solve? The ways that we represent problems to learners in the problem statement will affect how problem solvers mentally represent problems that they are trying to solve. That is the goal—to get learners to construct a meaningful, conceptual model of the problems they are trying to solve. However, that problem representation is only one source of influence, as are each of the perspectives represented by the different cases. In order for students to deeply understand the problem, they should construct one or more models of the problem. For example, if the policy problem that students are trying to solve addresses smoking policies such as no-smoking environments, restrictions on tobacco advertising, taxes on tobacco products, reducing healthcare costs, or similar policies, then students may want to construct a systems model (see Chapter 19) of the smoking population (see Figure 6.3). This model (produced with Stella, a systems dynamics modeling tool (see Chapter 19), depicts the dynamic relationships between different factors affecting the population of smokers. Systems-dynamics modeling tools enable learners to add or subtract factors and to test the effects of changes in those factors. These tools also enable the students to test their models by changing parameter values and noticing the effects. Figure 6.4 illustrates the output of the model when additional antismoking campaign money is contributed. By changing values, the model produces different outputs, allowing students to test alternative solutions. The outcomes of such models may also be used as evidence to support student-constructed arguments in support of their preferred solutions (described later in this chapter).

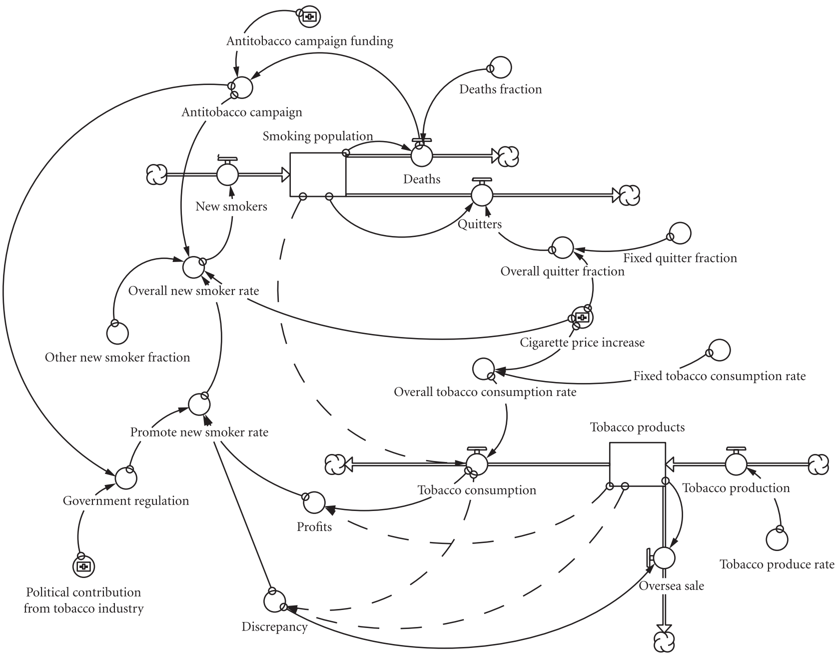


Figure 6.3 Systems dynamics model of smoking population.

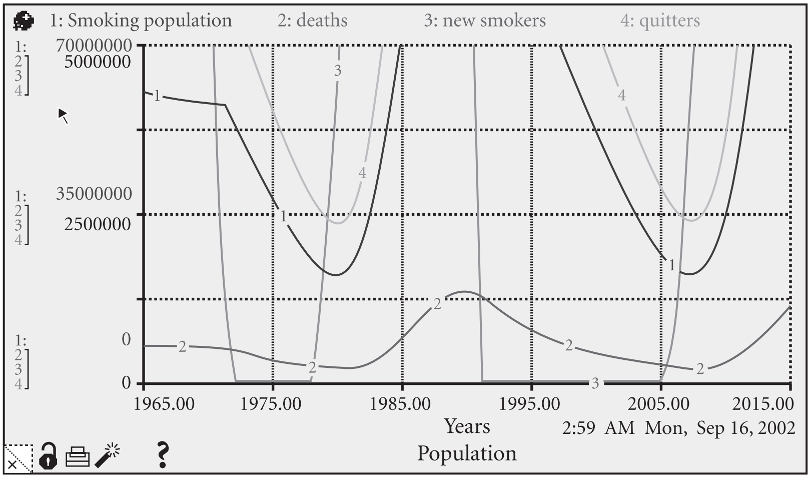


Figure 6.4 Output of systems dynamics model.

HOW DO LEARNERS GENERATE SOLUTION OPTIONS

As mentioned before, for the Kosovo crisis, several solutions were suggested, including declaring Kosovo an interim international protectorate, establishing Kosovo as an independent state, negotiating with Serbia conditions for the partition of Kosovo with some parts to fall under Kosovar Albanian rule and some parts under Yugoslavian rule, and making Kosovo part of a greater Albania. Learners may be required to generate additional plausible solutions, using the provided solutions as models for how to articulate a meaningful solution.

Solutions may also be generated by learners, based on the models that they construct. As indicated before, the models that learners construct may provide relevant evidence in support of their preferred solution. Their models suggest the factors that need to be addressed when learners construct arguments in support their preferred solution.

In their description of policy problem solving, Patton and Sawicki (1986) recommend that policy decision makers must display and distinguish among alternative policies, a process that is supported by the construction of decision matrices (see Chapter 3 for a more extensive description of decision matrices). The solutions that are provided may be analyzed using a decision matrix. Any solutions that learners generate should also be added to the matrix to facilitate argument construction (described later). The point here is that decision matrices provide a useful format for articulating the dimensions of alternative solutions.

HOW DO LEARNERS GENERATE SCENARIOS FOR POLICY PROBLEMS?

Scenarios are quite simply "stories of possible futures" that help us to see the present and the future as a continuously evolving story (Ralston & Wilson, 2006). According to Ralston and Wilson, scenarios are descriptions of plausible alternative futures that provide different views of the future that describe its dynamic nature. The primary purpose of scenarios is to support strategic planning and decision making. A rich literature on scenario planning has evolved (e.g., van der Heijden, 2005; Geogantzas & Acar, 1995; Ralston & Wilson, 2006; Ringland, 2006).

The first company to institutionalize scenarios was either the RAND Corporation or Royal Dutch Shell Oil (opinions differ). Shell Oil, like most oil companies, was sent reeling from the drastic increases in the price of crude oil in the 1970s, so they began using scenarios to predict what was increasingly becoming an uncertain future.

Subsequently, hundreds of international companies began constructing scenarios to aid in their strategic planning. Scenario planning is an activity carried out almost universally by strategic managers in corporations. In fact, scenario planning is the single most commonly used conceptual tool used by strategists (van der Heijden, 2005). Companies use scenario planning to assess their own abilities and to make policy decisions.

Scenarios are represented in different ways. First, they consist of stories (Chapter 12) about potential futures, rather than pasts. Second, they consist of causal models (Chapter 17) that may be represented as influence diagrams (see Chapter 17) or as mathematical models that can be represented as spreadsheets or systems dynamics models (see Chapter 20 for descriptions of those). Finally, scenarios accommodate multiple perspectives or events (Chapter 13) that are conveyed as uncertain events in the stories and causal models. The story holds the scenario together. The plot line of the story is determined by the causes and their effects on different events and outcomes that are both internal and external to the organization.

The scenario-planning process can be quite complex. After forming the scenario-building team, the team gathers data and projections, identifies the key decision factors, and identifies the critical forces and rivers that may affect outcomes (Ralston & Wilson, 2006). In order to construct the scenarios, the scenario team must assess the importance and the uncertainty of the forces and drivers, identify the most important and most uncertain factors, and then write stories about possible outcomes. The heart of the scenario-planning process is placing factors on a 2 × 2 scenario matrix (important vs. less important factors and forecastable vs. uncertain factors). Scenarios are primarily from the important, uncertain factors. Finally, the company examines the alternative futures and makes the decision that is most likely to accommodate uncertainties (Ralston & Wilson, 2006). This process is used by companies to construct multiple scenarios, each with a different set of predictions based on key factors. It is essential that multiple scenarios are constructed. These multiple scenarios will provide decision makers with decision options.

HOW CAN LEARNERS ARGUE FOR THEIR SOLUTIONS?

Policy problems are dialectical in nature, in which two or more conceptualizations of the problem lead to different solutions. Because only a single solution may be accepted and implemented on most cases, it will be necessary for students to construct arguments in support of their chosen solution. Developing cogent arguments to support divergent solutions engages not only cognition and metacognition of the processes used to solve the problem but also awareness of the epistemic nature of the process and the truth or value of different solutions (Kitchner, 1983). In the Kosovo crisis, for example, there were many possible solutions that were suggested and others that learners may have generated. Requiring students to develop an argument for their choice is tantamount to problem solving. That is, it provides very useful assessment data to help the teacher determine what and how much the learners know.

Chapter 20 explains the fundamentals of argumentation more extensively. After collecting all of the perspectives deemed appropriate for constructing an argument, learners may first want to determine their argumentative goal. Will they engage in an adversarial comparison of alternative solutions by forwarding their own arguments and rebutting others in order to select the best solution suggested? Or will learners seek a compromise solution that combines merits of more than one solution (“Is there a compromise or creative solution?”). Or will learners attempt to evaluate alternative arguments and support the stronger argument based on the weight of evidence for that solution (“Which side is stronger and why?”)? The goal will determine the argumentative strategy.

In most policy problems, different parties promote their own agenda, so the strategy usually becomes somewhat adversarial. If that is the case, then, as suggested in Chapter 20, learners’ arguments may be prompted by a series of questions, such as

1. What do you think the best solution is?
2. How would you prove that this is the best solution?
3. What might somebody else, who does not agree with you, think is a better solution?
4. What could you tell him or her to show he or she is wrong?
5. What might somebody else say to show that your solution is wrong?
6. What could you tell him or her to show he or she is wrong?

Learners may also be required to complete a Vee diagram (see Chapter 20) summarizing the information generated by these questions.

Question prompts may also focus on more general, metacognitive reflection on the nature of the argument in order to evaluate alternative solutions. For example, learners may be prompted for a series of reflective metacognitive prompts (Kitchner & King, 1981; see also Chapter 21), such as

- Can you ever know for sure that your position is correct? Will we ever know which is the correct position?
- How did you come to hold that point of view? On what do you base it?
- When people differ about matters such as this, is it ever the case that one is right and the other wrong? Is one opinion worse and the other better?
- How is it possible that people can have such different points of view?
- What does it mean to you when the experts disagree on this issue?

In addition to providing a purpose for examining and analyzing the multiple perspectives that you provide in your policy-analysis learning environment, learner-generated arguments also provide a powerful form of knowledge assessment. In order to construct a coherent argument, learners must construct robust mental models of the problem and apply metacognitive strategies in articulating a more compelling argument. Those arguments may be constructed as essays, debates, or role-plays, depending on the nature of the environment and the context in which it is implemented.

7

DESIGN PROBLEM SOLVING

Design is the most complex and ill-structured kind of problem solving. Design is a ubiquitous professional activity. In the fields of engineering, architecture, education and training, music, art, theater, writing, interior decorating, agriculture, computer science, marketing, and nearly every professional endeavor, professionals design products, creations, processes, systems, activities, models, and a host of other outcomes. Most professionals are engaged in some form of design:

- writing software programs;
- designing a building;
- designing a new car or any of its 10,000 components;
- writing a concerto or musical score, writing a book, play, short story, article, or poem;
- creating a marketing campaign for a new product;
- creating a new food product;
- designing a storefront display;
- decorating your home's interior or exterior;
- decorating a cake.

These and thousands of other jobs and tasks engage design problem solving.

Needless to say, these different kinds of design vary in process, assumptions, and methods. That is, there are different kinds of design problems. According to Brown and Chandrasekaran (1989), Class-1 design problems are open-ended, creative activities where the goals are ill specified and there is no effective design plans specifying the sequence of actions to take for producing a design model. Class-1 design problems are not routine, requiring an innovation or new product. They are very ill structured. Class-2 problems use existing, well-developed design and decomposition plans (e.g., designing a new automobile). Class-3 designs are routine where design and decomposition plans are known as well as actions to deal with failures (e.g., writing a computer program).

Historically, design has been conceptualized as a linear set of phases through which a designer progresses. In this chapter, I first describe these normative models of design and later look at how people actually design before proffering my own conception of the design process.

WHAT ARE NORMATIVE THEORIES OF DESIGN?

Design problem solving is most often chronicled in the disciplines of engineering design, product design, architectural design, and instructional design. These activity systems are quite distinct, as are the nature of the design processes in which engineers, architects, and instructional designers engage. The largest body of research and writing on design comes from engineering design (e. g., Cross, 2000; Petroski, 1996; Vincenti, 1990).

Given that design problems are among the most complex and ill structured of all problems (Jonassen, 2000c), most disciplines attempt to define normative phase models for creating, constructing, and communicating designs. These models are most commonly recommended for the disciplines of engineering, product design, and instructional deign. For example, the engineering design process includes the following phases according to Dym and Little (2004):

1. **Problem definition**: from the client statement, clarify objectives, establish user requirements, identify constraints, and establish functions of product by providing a list of attributes.
2. In the **conceptual design** phase, establish design specifications and generate alternatives.
3. In the **preliminary design**, create model of design and test and evaluate the conceptual design by creating morphological charts or decision matrices (see Chapter 3).
4. During the **detailed design**, refine and optimize the chosen design.
5. For the **final design**, document and communicate the fabrication specifications and the justifications for the final design.

In a similar conception, Ullman (2003) described the mechanical design process in terms of the following activities:

1. **Project definition and planning**: form team, develop tasks, research market, estimate schedule and cost, and secure approval of project plan.
2. **Specification definition**: Identify customers, generate customers' requirements, evaluate competition, generate engineering specifications, set targets, and secure specification approval.
3. **Conceptual design**: Generate concepts, evaluate concepts, make concept decisions, document and communicate, and secure approval of conceptual design.
4. **Product development**: Generate and evaluate product in terms of performance, cost, and production, make product decisions, and document and communicate.

Restated, these phases comprise the process of exploration, generation, evaluation, and communication (Cross, 2000). There is evidence to support these prescriptive theories. Ball, Evans, Dennis, and Ormerod (1997) found that designers actually implemented a highly systematic solution-development strategy that deviated only a small degree from a normatively optimal top-down and breadth-first method.

Another prominent design venue is new product design in business. Their models for design closely resemble engineering design models. One of the more elaborate models, proffered by Cooper and Kleinschmidt (1986), includes the following processes:

1. initial screening to allocate funds for exploration;
2. preliminary market assessment;
3. preliminary technical assessment (Can we do it?);
4. detailed market study (market research);
5. business and financial analysis (Can we afford it?);
6. product development (design and development of prototype);
7. in-house product testing;
8. customer tests of product in the field;
9. test market or trial sell;
10. trial production;
11. precommercialization business analysis;
12. production start-up;
13. market launch.

In all of the new product-development models, the new product is transformed from an idea into a possibility that is assessed into a test phase and a final commitment. Despite its ubiquity in teaching product-design processes, this model of product design has been the focus of very little empirical research.

The final prominent design venue that I will describe is instructional design. Instructional design has historically been described in normative phase models. Based on an analysis of forty instructional design models, Andrews and Goodson (1980) cited fourteen tasks that were common to those models, including formulation of goals and subgoals, developing assessments, analyzing tasks, sequencing of goals and subgoals, analyzing learner attributes, formulation of instructional strategies, selecting delivery media, developing instructional materials, trying out materials, developing materials, assessing needs, considering alternative solutions, identifying constraints, and costing instructional programs. The core elements to all of those models are summarized in the ADDIE model (analysis, design, development, implementation, and evaluation (Gustafson & Branch, 1997). That is, instructional designers first engage in analysis, which may include needs assessment, learner analysis, task analysis, and context analysis. Having collected that information to justify their designs, instructional designers design the instruction by assembling content and instructional strategies. Following design, they develop or produce the instructional materials (similar to new product development) which they implement and formatively and summatively evaluate its effectiveness. These phase models also confound project management and workflow decisions with design decision making. These efforts have led to a rather linear representation of design. Unfortunately, instructional design has been one of the last fields to abandon linear models in favor of nonlinear, design-driven models.

An important assumption of all of these design models is that the design process is discipline and context neutral; that is, design is largely independent of the domain and context in which it occurs. On the other hand, Rowland (1993) argued that design is very much influenced by what it is that people design. That is a very reasonable assumption, which causes me in the next section to ask how do people really design.

HOW DO PEOPLE ACTUALLY DESIGN?

The normative phase models of design just described infer that design is a predictable process, that if the process is followed the way it is supposed to be, that an optimal solution will result. There exist several reasons why that conclusion is problematic.

First, the goal of most designers is not an optimal solution. Why?

Optimal solutions cannot even be defined let alone achieved for most ill-structured problems (see Chapter 1). Given any problem for which a design is required, there are an infinite number of possible solutions. Although only a subset of those solutions may be viable, determining which is optimal can seldom be accomplished. Despite the apparent goal of finding an optimal solution, design problems usually have vaguely defined or unclear goals, multiple criteria for evaluating solutions, and many unstated constraints that must be discovered during the design process. Ultimately, the designer attempts to please the client. However, because the criteria for an acceptable design are usually unstated, rather than optimizing a solution, designers most often seek to satisfice (Simon, 1955), a strategy that attempts to meet criteria for adequacy rather than identifying an optimal solution. Design problems often require the designer to make judgments about the problem and defend them or express personal opinions or beliefs about the problem, so ill-structured problems are uniquely human interpersonal activities (Meacham & Emont, 1989).

Second, designers seldom perform all of the activities defined by normative design processes. In their layers-of-necessity model, Tessmer and Wedman (1990) argued that based upon time and resource constraints, the developer chooses a layer of design activities to perform. The layer of activity chosen depends on the necessities of the project. For time-pressured design situations, designers will perform the activities on the simplest layer. If additional time or resources are made available, the designer may choose to engage more sophisticated design processes on a deeper layer.

Third, although some argue that design, as it is practiced by experts, is structured and heuristic and guided by accepted principles (Silber, 2007), I argue that design is ill structured and that the primary thinking process that all designers (including experts and non-experts) employ is decision making that occurs in cycles. Decisions are driven less by accepted principles than they are by constraint satisfaction and beliefs, some of which are culturally accepted and others that are context specific. That is, design is an iterative process of decision making and model building. "The principal role of the designer . . . is to make decisions. Decisions help to bridge the gaps between idea and reality . . . decisions serve as markers to identify the progression of the design from initiation to implementation to termination" (Marston & Mistree, 1997, p. 1). Clearly, decisions require thinking processes, as suggested by Silber, but decision making as a goal is far different to rule using. Many artists and architects refute this assumption, claiming that it is too reductive and ignores the roles of creativity and inspiration in design. Ultimately, however, even creative designers must make fundamental decisions about materials, functions, and a host of other design factors.

Most design decisions, especially instructional design decisions, are based on multiple constraints and constraint operations in the design space, not an agreed upon set of rules and heuristics, as suggested by Silber (2007).

"Design is a quintessential cognitive task" (Goel & Pirolli, 1992, p. 395). The purpose of most designs is to construct an artifact that (Mostow, 1985):

- satisfies functional requirements;
- meets implicit and explicit performance requirements;
- satisfies implicit and explicit design criteria (style, simplicity, testability, maintainability, reusability, modularity, etc.);
- satisfies restrictions or constraints on design process itself (e.g., time, cost, tools available).

The design process consists totally of reasoning about constraints in order to determine parameter values (Brown & Chandrasekaran, 1989). Gross (1986) introduced the idea of design as constraint exploration. Constraints are the formal and informal "rules, requirements, conventions, and principles that define the context of learning" (Gross 1986, p. 10). Designing as a process of exploring and expressing constraints includes operations such as describing and structuring constraints and objectives, exploring fixes, resolving conflicts, and comparing alternatives (Gross, Ervin, Anderson, & Fleisher, 1988). Objectives are well established in the instructional design literature. Constraints in instructional design include:

- technologies available, preferred or accessible;
- economic (funds) and talent available;
- political or organizational mores and rules;
- environmental factors;
- learner characteristics;
- learning goals;
- physical context in which instruction delivered.

Constraints are rarely, if ever, identified completely at the beginning of the design process, as implied by the analysis phase at the beginning of the ADDIE model. Rather, they emerge during each cycle in the design process. Designers make decisions based on the constraints as they emerge. What makes design an iterative process is simultaneous constraint satisfaction and constraint propagation. As constraints are identified and accommodated, new ones appear. As constraints are addressed during each cycle, the degrees of freedom decrease, converging on a solution that satisfies the greatest number of constraints. Figure 7.1 conceives of the design process as a spiral of decisions. At the beginning of the design process, there are many degrees of freedom, that is, a relatively large number of options. As design decisions are made, those degrees of freedom are restricted by the decisions that have been made previously.

Design decisions are influenced not only by cognitive activity but also by affective dispositions. As depicted in Figure 7.1, design decisions are influenced by beliefs that are often replete with personal, cultural, or organizational biases. Beliefs are conceptual frameworks that are amalgamations of cognitive representations that are influenced by affective judgments. All designers make such judgments. For example, engineers talk about elegant solutions. Most artists and architects repeat signature designs that reflect their personal beliefs about form. Designs from different cultures appear quite different. For example, Finnish architecture is far more simple in its appearance than Portuguese architecture. The cultures vary dramatically. Designs are also influenced by

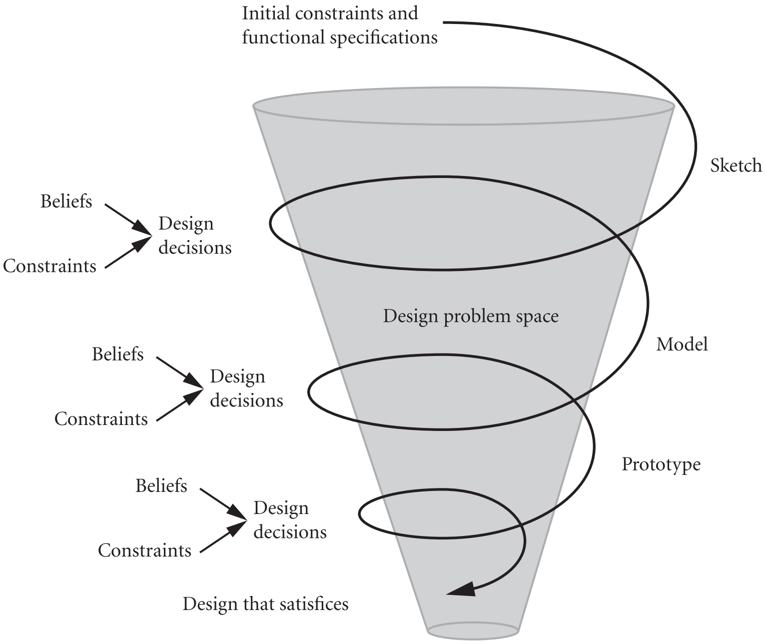


Figure 7.1 Iterative design process.

organizational norms. For example, software from Microsoft appears and functions similarly because of organizational beliefs. Too often, instructional design decisions are most affected by unsubstantiated beliefs about the efficacy of the newest technology. For example, during the mid-1980s, interactive video solutions to learning problems were disproportionately chosen because that technology was the newest and most innovative. Early in the next decade, multimedia solutions were the most common choice. In the mid-1990s, Internet websites became the default solution. Nowadays, games have become the solution of choice. During each technology epoch, favored solutions to learning problems have been implemented in spite of constraints that may have contradicted them. Ask any instructional designer to justify all of the design decisions that were made. Most will be unable to provide empirical or theoretical justifications for many of the decisions.

Design is also a process of model building. As design decisions are made, designers begin to construct sketches that morph into models that morph into prototypes (see Figure 7.1). Engineers and architects most often begin by creating a drawing. As decisions are made about the design, the design model expands as the decision-making contracts (see Figure 7.1). The initial drawing may be converted to a CAD drawing, a computational model, or a three-dimensional model. Instructional designers may begin by producing a storyboard and later converting that into a prototype of the learning environments. That is, as design decisions are made, degrees of freedom decrease (deceasing spiral in Figure 7.1) while the model becomes more elaborated. These models should reflect the functional requirements of the design as elaborated during the cycles of decisions.

The goal of design is satisficing, not optimization. Although designers talk about optimization, design solutions are seldom, if ever, the best solutions (Marston & Mistree, 1997). In reality, designers are usually unable to articulate what an optimal solution is.

Many years of research and reflective instructional design experience have convinced me that instructional design is a cyclical process rather than a sequence of phases. ADDIE and other phase models of instructional design imply that design is a relatively linear process and that adaptations in designs occur only after implementation of a design that has been developed and implemented. Rather, beginning with the analysis phase, the design process iterates and changes with each cycle of design. Those design cycles are more micro-level than macro-level.

HOW CAN STUDENTS LEARN TO SOLVE DESIGN PROBLEMS?

What implications does this model have for preparing designers? The most important lesson is that successful design must address the constraints imposed by the context, and those constraints emerge throughout the design process. Designers address those constraints in a series of decisions. Teaching students a set of principles and heuristics, especially if done in the absence of context, will not help students learn to make decisions or to design. Instructional design models, including ADDIE, are based on principles that are, intentionally by design, applied uniformly in all contexts. That is why instructional design is so often criticized. Whatever model of instructional design is used by designers, the design team should explicitly identify all of the decisions that are made in each cycle of the design process. For each design decision, designers should identify the constraints that are being addressed in the decision. Additionally, designers must articulate their rationale for the decision made by associating their choices with appropriate theories, empirical research, and previous experience. This entire book is replete with rationales for making design decisions. For each decision, designers should examine that decision in light of previous decisions in the design projects to ensure consistency in decision-making. If decisions contradict previous decisions, substantive reasons should be given. Finally, for each decision, designers should articulate personal and organizational beliefs and biases about design preferences. While this can be difficult, it can be supported by examining previous designs for common characteristics. Although beliefs should not be completely ignored, they need to be compared with theory, research, or previous experience.

The next implication is to resist the temptation to jump to a final solution based on a little bit of analysis. Analysis is a process that pervades design, and it does not always occur in the front end. Rather, constraints emerge throughout the process and need to be addressed when they do emerge.

WHAT ARE THE COMPONENTS OF A DESIGN-PROBLEM LEARNING ENVIRONMENT?

These are the minimal requirements for design of problem-solving learning environment to support learning to solve design problems.

How Can Problems to Solve Be Used?

The focus of any problem-solving learning environment is the problem to solve. Design problems are usually conveyed as stories, where the initial constraints and perspectives are included (See the ID Casebook [http://curry.edschool.virginia.edu/go/ITcases] for examples of instructional-design problems.

How Can Prior Experiences Be Used?

As indicated in Chapter 12, when faced with a problem to solve, people immediately attempt to recall a similar problem. Failing that, they tell a story of their problem to someone else who is reminded of an experience they have had. The problem solver tries to reuse the prior experience to solve the current problem. Prior experiences have profound effects on problem solving. In the case of design problems, that effect may not always be positive. Prior experiences are replete with biases, which affect current deigns. It is not uncommon for a designer to reuse a previous design, regardless of how well it applies to the current design problem.

How Can Case Studies Be Used?

Students should also study case studies of similar design experiences to help them to construct problem schemas for certain kinds of design problems. An untested but potentially powerful way to study those case studies would be to analyze think-aloud protocols of designers at work or stories told by designers about their cases. In a series of studies (Atman & Bursic, 1998; Atman, Chimka, Bursic, & Natchtmann, 1999; Atman & Turns, 2001) showed how protocol analysis of student think-aloud transcripts while solving design problems could be used to assess student design processes. The researchers developed coding schemes, chose a design problem, collected student think-aloud protocols (Ericsson & Simon, 1993) while they solved the problems and then analyzed and interpreted the results. They developed a coding scheme for analyzing the protocols, which included classes:

- Identify need for solving problem.
- Identify problem and constraints and criteria.
- Gather information beyond that provide in the problem statement.
- Generate ideas for solutions.
- Develop a model of the problems.
- Determine feasibility of solutions.
- Evaluate alternative solutions.
- Make a decision.

- Communicate decision and instructions to others.
- Implement solution and drawing implications.

The researchers classified each sentence according to this scheme and found that more experienced designers produced better designs, because they collected more information, considered more alternatives, and transitioned between design processes more readily. These codes were generated for the study based on textbook descriptions of engineering design processes. Needless to say, problem solving in different domains or different kinds of problem solving would require different sets of codes. Also, different coding systems emphasizing different structural properties may be used to analyze the same problem-solving protocols.

In an extension of that work, students assumed the roles of researchers as they coded think-aloud protocols of design processes (Scott, Turns, & Atman, 2001). The engineering students worked in pairs to analyze the think-aloud transcripts of problem solving where more experienced designers designed a ping-pong ball launcher or a playground, for example. Their analysis of practice helped those learners better to understand the design process, to appreciate the complexity and ambiguities implicit in the design process, to build consensus and to collaborate, and to use alternative strategies for designing. Although the purpose of these studies was to study the coding and arbitration processes among coders, it is probable, although untested, that verbal protocol analysis of problem solving that use codes that focus on necessary structural properties of problems will facilitate the appropriate reuse of cases regardless of the sequence of their presentation. Coding protocols provides an alternative to questioning and structural mapping (described next) and will support generalization and transfer among cases.

How Can Argumentation Be Used?

As demonstrated in Chapter 3, a primary outcome from solving decision-making problems is an argument justifying the decision that is rendered. If design is an iterative process of decision making, then students must learn to develop a justification for each decision that they make.

How Can Modeling Be Used?

As indicated before, modeling is key to the design enterprise. Constructing models using different tools (see Chapter 20) will be key to the design process. Which kind of modeling tool should be used will depend on the nature of the design being produced.

PART II

CASES: THE BUILDING BLOCKS OF PROBLEM-SOLVING LEARNING ENVIRONMENTS

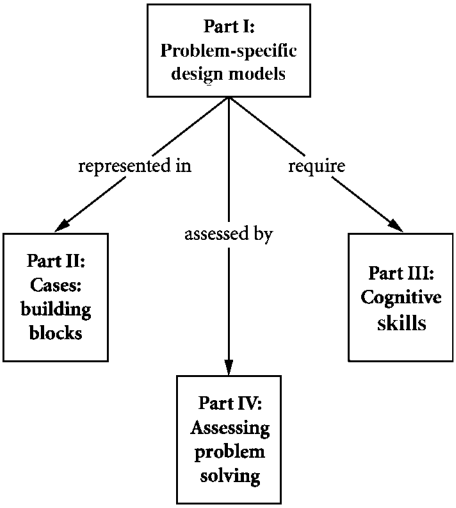


Figure II.1

As indicated at the beginning of the book, cases are the building blocks of problem-solving learning environments (PSLEs). That is, different kinds of problems and the support needed to learn to solve them are represented as cases. Learning to solve problems in formal education contexts invariably involves the use of cases. Various forms of problem-based learning, problem-centered instruction, case studies, case-based teaching, case-based instruction, and case-based learning (hereafter generically referred to as case-based learning) have been developed to engage or support learning how to solve different kinds of problems.

Unfortunately, the meanings ascribed to these case-based learning approaches vary as widely as the methods that have been developed. Conducting research and disseminating innovations in case-based learning pedagogies have been hampered by this divergence of interpretations and associated methods. The confusion surrounding case-based learning approaches emanates from two important components of case-based learning: the content and form of cases and, more importantly, the function of cases. Concerns with case-based learning result, I believe, from the fact that most of the literature focuses on the form of the cases not their purpose or function. In this part of the book, I will introduce seven different kinds of cases, each of which are described in separate chapters.

What constitutes a case? The concept "case" has many interpretations. To professionals, a case represents practice examples, such as a "case of measles" to a physician or a "case of libel" to an attorney (Schön, 1983). For the purposes of this book, a case is an instance of something. In Part II of this book, cases fulfill the following learning functions:

Chapter 8	Cases as problems to solve are instances of problems that will be the focus of learning.
Chapter 9	Cases as worked examples are instances of the process for solving well-structured problems.
Chapter 10	Case studies are instances of how others have solved ill-structured problems.
Chapter 11	Cases as analogies are instances of structurally similar problems.
Chapter 12	Cases as prior experiences are descriptions of previously solved problems that are reminded by the problem to be solved.
Chapter 13	Cases as alternative perspectives are instances of different perspectives on the problem to be solved.
Chapter 14	Cases as simulations are interactive instances of the problem to be solved that can be experimented with by learners.

So, anything from a sentence-level or pictorial example to a complex, multi-page case study to a complex simulation of a problem constitutes a case.

How should these cases be used? The assumption of this book and of problem solving is that learning should be anchored in an authentic problem that is relevant to the learner. Learners need to develop, explain, and defend a solution to the problem. The problem

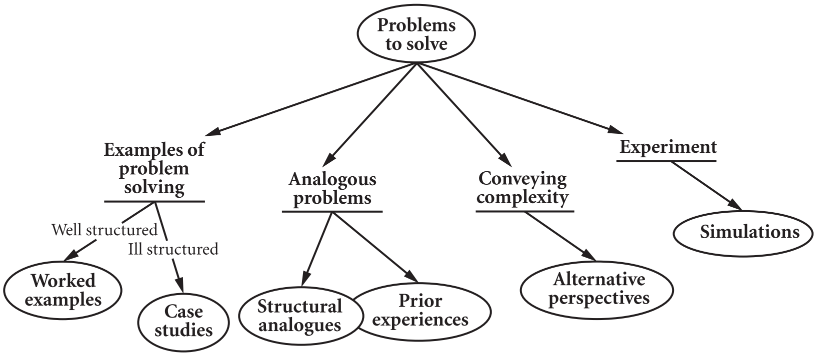


Figure II.2

to be solved is represented as a case, and cases are used in various ways as instructional support. As illustrated in Figure II.2, worked examples, case studies, structural analogues, prior experiences, alternative perspectives, and simulations are all examples of cases that may be embedded in PSLEs to support the solution of the problem to be solved.

8

CASES AS PROBLEMS TO SOLVE

Although analysis of case studies (see Chapter 10) may be the most common application of cases, cases as problems to solve represent the focus of this book. Problems to solve are the focus of any problem-solving pedagogy. The use of problems as the focus of learning is supported by problem-based learning principles. According to those principles, learning is anchored in an authentic problem. Traditional models of instruction assume that students must master content before applying what they have learned in order to solve a problem. Problem-based learning reverses that order and assumes that students will master content while solving a meaningful problem. In most educational venues, that represents a paradigm shift. Efforts to adopt principles of problem-based learning are justified because I believe that problem-based learning is the most significant curricular innovation in the history of education. That is, if implemented properly, problem-based learning could have a more significant impact on learning in schools that any previous innovation.

WHAT DO CASES AS PROBLEMS TO SOLVE ASSUME?

Problem-based learning (PBL) as a curricular innovation emerged in medical education (Barrows & Tamblyn, 1980). With its roots in case-study methods of instruction (see Chapter 10), PBL has also become increasingly popular across disciplines in higher education and K-12 education settings (Barrows, 2000; Dochy, Segers, van den Bossche, &

Gijbels, 2003; Gallagher, Stepien, & Rosenthal, 1992; Hmelo, Holton, & Kolodner, 2000; Hmelo-Silver, 2004; Torp & Sage, 2002).

PBL is an instructional strategy. That is, it is an instructional solution designed to improve learning by requiring students to learn content while solving problems. As such, PBL is:

- **problem-focused**, where learners begin learning by addressing simulations of an authentic, ill-structured problem;
- **student-centered**, because faculty cannot dictate learning;
- **self-directed**, where students individually and collaboratively assume responsibility for generating learning issues and processes through self-assessment and peer assessment and access their own learning materials;
- **self-reflective**, where learners monitor their understanding and learn to adjust strategies for learning.

The PBL process normally involves the following steps:

1. Students in groups of five to eight encounter and reason through the problem. They attempt to define and bound the problem and set learning goals by identifying what they know already, what hypotheses or conjectures they can think of, what they need to learn in order to better understand the dimensions of the problem, and what learning activities are required and who will perform them.
2. During self-directed study, individual students complete their learning assignments to understand the problem and its possible solutions. They collect and study resources and prepare reports to the group.
3. Students share their learning with the group and revisit the problem, generating additional hypotheses and rejecting others based on their learning.
4. At the end of the leaning period (usually one week), students summarize and integrate their learning.

PBL was implemented in the medical-school curriculum at the University of Missouri in 1997. Replacing the basic sciences approach to learning medicine, students from their first day work in groups to solve diagnostic medical problems such as that displayed in Table 8.1. Note that this case is somewhat structured with question prompts. During later stages, those prompts are removed.

Throughout their two-year medical program, students learn anatomy, physiology, biochemistry, immunology, etc., while diagnosing patient problems, such as that in Table 8.1. In the first four years of the

Table 8.1
First year PBL medical case, with permission, Michael C. Hosokawa, author

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All in the Family

Session 1

Mrs. Samson comes to the clinic today because she has felt fatigued. About a month ago, she said that she began to notice that she was tired most of the time.

The doctor asks if there have been any stressful times during the last month that might be causing fatigue. She says her life has been pretty normal for a mother of two teenagers. She laughs.

You ask if she started an exercise program or if she has been working especially hard. She says that she wishes she could start exercising, but she does walk at the mall three mornings each week with a friend.

You ask if she has been eating a balanced diet or if she has changed her diet. She says she probably eats a little too much, but she does get a balanced diet.

Why is the physician asking these questions?

Are there other questions you would ask Mrs. Samson?

Patient History

Mrs. Samson is a 36 y.o. patient who has had one previous visit for a sprained ankle. She is married and has two children, a boy 15 and a girl 13. Both pregnancies were normal. Deliveries were vaginal without incident. Mrs. Samson works as the branch manager for a local bank. She has a bachelors degree in finance and a MBA. She has been married for 18 years. Her husband is a high school principal. Mrs. Samson is active in her church and volunteers at the senior citizens center once a week to help with the meals program.

What would you do next?

Physical Exam

Ht. 170 cm Wt. 67 kg P 73 BP 122/80 mmHg R 16

Temp 36.8 degrees C

HEENT: Tympanic membranes and external auditory canals clear bilaterally. Pupils equal, round and reactive to light and accommodation. Nasopharynx clear, no lesions, no erythema or exudate. Dentition normal. Neck supple, no thyromegaly, no lymphadenopathy.

Lungs: Clear to auscultation

Heart: Regular rhythm

Breasts: No masses

Abdomen: Nontender, bowel sounds normal, liver and spleen nonpalpable, no masses

Extremities: Pulses intact, no edema, no cyanosis, no joint abnormalities

Neurologic: Reflexes symmetrical and 2+

Pelvic exam: Normal

Make a list of terms you do not understand. How would you find out what these terms mean?

What are your conclusions based on these physical exam results?

The doctor asks Mrs. Samson if she has had any other symptoms other than fatigue.

(*Continued Overleaf*)

Table 8.1
Continued

All in the Family

Mrs. Samson pauses and looks at the floor. “Well, I have noticed streaks of blood when I have a bowel movement.” She seems embarrassed. “This has happened several times each week. I’ve been sort of worried about this because my brother who was 9 years older died of intestinal cancer last year and my father died of cancer of the large intestine when he was 50. I know there were other people in my family with cancer, but I don’t know what kind they had.”

The doctor tells Mrs. Samson that he wants her to go to the lab in a few minutes to draw blood for some tests and there is one more test I want you to have. “The nurse will give you a packet to take home. The test is called a homoccult test and it is to determine if there is blood in the stool. The nurse will explain how to do the test.”

Mrs. Samson seems confused. She says, “Well, I can see blood.” The doctor explains, “you want to know if blood is there even if you cannot see it. I am going to schedule you for another appointment in about two weeks. I am also going to schedule you with another doctor for a colonoscopy. The nurse will set up the appointment, tell you how to get to the clinic and give you some instructions. With the colonoscope, the doctor can look at the inner part of your intestine and maybe find the cause of the bleeding.”

Lab Results

Heme Profile: Hct 35%
Hgb 12.2 gm/dL
WBC 8400/mm^3
MCV 86μ^3
MCH 30$\mu\mu^3$
MCHC 32%
WBC Diff:
neuts 62%
lymphs 34%
monos 4%
platelets 1850,000/mm^3
SMAC:
glucose 145 mg/dL
Na 140 mEq/L
K 4.6 mEq/L
Cl 104 mEq/L
BUN 17mg/dL
Creatinine 1.0mg/dL
Calcium 917mg/dL
Phosphate 3.8mgdL
Protein 7.2 gm/dL
Albumin 4.1 gm/dL
Uric Acid 5.3 mg/dL
cholesterol 225 mg/dL
alkaline phos 95 U/L
total bilirubin 1.2 mg/dL
direct bilirubin .2 mg/dL
AST 30 U/L
ALT 35 U/L
LDH 142 U/L
CK 76 mU/ml

What is your differential diagnosis. What is a differential diagnosis?
What is the structure of the digestive tract. How does it function?
What is a hemoccult test? What is a colonoscopy? What is a sigmoidoscopy?

Research Break

Session 2

Mrs. Samson returns to the clinic two weeks later. The doctor tells her that the hemoccult test was positive indicating that she had blood in the stool. She has been scheduled for her colonoscopy next week.

Dr. Radford performs the sigmoidoscopy. Following the procedure, the doctor meets Mrs. Samson in the conference room. He explains that he was able to see numerous polyps on the surface of the large intestine. He wants to do another test, but based on her family history and the tests he has done, he is pretty sure Mrs. Samson has a disease called familial polyposis coli.

Research Break

Session 3

Using P as the symbol for the dominant gene for familial polyposis coli and p as the symbol for the recessive normal gene, the doctor explains to Mrs. Samson how this disease has affected her family. There is no evidence of colon cancer in her husband's family.

What are the chances that Mrs. Samson's two children will have familial polyposis coli?

What if this disease were transmitted by a recessive gene?

Using the following symbols, work out a pedigree of Mrs. Samson's family.

Mrs. Samson's father died of colon cancer. Her mother is living and healthy. Her brother died of colon cancer. Her younger sister, age 32, is healthy. Her brother has one teenage child, 17 years old. The brother is divorced and Mrs. Samson does not know much about her brother's ex-wife. Her younger sister has two children. She has no other siblings. Her uncle (her father's brother) is living and has high blood pressure and diabetes. Mrs. Samson's grandparents on her father's side of the family both died of heart disease in their sixties. Mrs. Samson's grandparents on her mother's side of the family both died in an automobile accident in their fifties.

What is your treatment plan for Mrs. Samson?

program, students learning through PBL achieved higher scores on the Medical Licensure Examination than students who completed their program under the traditional curriculum (Blake, Hosokawa, & Riley, 2000). That trend was continued in the following years as PBL students generally outscored traditional students on the exam (Hoffman, Hosokawa, Blake, Headrick, & Johnson, 2006). In addition to improved exam scores, graduates received improved evaluations from residency program directors and preferred selections for residencies. PBL at Missouri better prepares graduates with the knowledge and skills that are needed to practice within a complex healthcare system.

A great deal of research has generated mixed results for the effects of PBL. Although early studies showed few advantages and some disadvantages for PBL, more contemporary research on PBL has shown that PBL students:

- consistently retain knowledge, especially more principled knowledge, for longer periods of time than students in a traditional curriculum;
- apply basic science knowledge and transfer problem-solving skills in real world professional or personal situations more effectively;
- become more self-regulated, lifelong learners.

(Hung, Jonassen, & Liu, 2008)

In a follow-up qualitative meta-synthesis of PBL research, Strobel and van Barnveld (2009) concluded that PBL resulted in superior long-term retention, skill development and satisfaction of students and teachers, while traditional approaches were more effective for short-term retention as measured by standardized board exams.

The rationale for problem-based learning is provided by two important contemporary theories of learning: situated learning and cognitive apprenticeships.

WHAT IS SITUATED LEARNING?

Learning in informal contexts in the everyday world is an activity-based and socially mediated phenomenon that occurs naturally in communities of practice (Lave & Wenger, 1991). Communities of practice are any naturally emergent group of people who work together to accomplish some activity usually involving social collaboration between individuals with different roles and experience. Rather than defining learning in terms of exam performance, knowledge is assessed by the individual's ability to participate in that community. Rather than learning content devoid of context and meaning, learning in communities of practice is focused on becoming a fully participating member of that community. That is, meaningful learning requires active and purposeful participation in a community that requires immersion in the activities of the community. The persons who learn the most naturally move toward the center of that community of practice (Lave & Wenger, 1991). In work groups, for instance, the most learned person is the one whose knowledge about how to do something is accessed most often. Learning in situ in communities of practice results from an interaction of learning processes, activity, and context.

When learning in situ, the knowledge that is constructed by learners is situated in the context in which it is learned. That does not mean that learning is always situated in authentic environments. Learning is always situated in some context or learning culture, even elementary, high-school or college classes (Brown & Duguid, 1994). So there exist everyday contexts (often called the real world) and classroom contexts (which also exist in the real world). Those in-school contexts and cultures define expectations for all types of intellectual and social performance. Whatever learning does occur is the product of the activity, context, and culture in which the learning occurs. Learners are required to negotiate meaning and to construct understanding in culture through collaborative social interactions (Brown, Collins, & Duguid, 1989).

Situated learning theory emerged from anthropological studies of informal learning (Lave & Wenger, 1991; Rogoff & Lave, 1984; Suchman, 1987). In an ethnographic study of refrigeration technicians in a supermarket chain, a former student of mine (Henning, 1998) found that learning in situ is mediated largely by conversations, primarily in the form of stories (see Chapter 12), that is, negotiation with each other and with the machines that these technicians were servicing and the tools they used to perform the services. Learning was also manifest in the social relationships among the technicians. Evidence of learning was manifest in their professional identities both within the community of practice and in the larger supermarket community.

WHAT ARE COGNITIVE APPRENTICESHIPS?

The oldest form of instruction is an apprenticeship, where a novice learns a trade by practicing the skills of the trade in the normal context of that trade using the normal tools of that trade. In formal education, however, students too often learn about professions but seldom learn how to transfer that learning to contexts in the everyday world. Apprentices do not have to transfer to new situations because they have learned to perform them in situ. In cognitive apprenticeships (Brown et al., 1989; Collins, Brown, & Newman, 1989), students are enculturated into authentic practice by solving problems and performing activities that simulate a real apprenticeship. Cognitive apprenticeships are pseudo-apprenticeships in which students learn to think and perform like masters. While serving cognitive apprenticeships, teachers and professors function as master, who:

- teach knowledge and skills in everyday and professional contexts;
- teach in multiple contexts and generalize across contexts;
- model processes and explain reasons for those processes;
- make information more explicit, helping learners develop knowledge about when and where to apply information;
- coach students (provide hints, feedback, and support) while monitoring students' progress;

- articulate students' actions, decisions, strategies to make knowledge more explicit;
- include reflection and analysis of students' performance;
- enable students to test various strategies and hypothesis and experience their effects;
- sequence instruction from simple to complex, using a variety of examples in different contexts.

Rather than learning to think like students, students serving cognitive apprenticeships learn to think like a master. Cognitive apprenticeships make explicit the decision making required to perform like a master. Often conventional apprenticeships (or mentoring) deal only with algorithmic problem solving, and any real decision making is left implicit. That is one of the reasons why apprenticeships are so inefficient and highly variable in their effectiveness.

PSLEs are perhaps the most appropriate medium for engaging students in cognitive apprenticeships. Engaging students in solving authentic problems to solve and supporting their problem-solving performance with cases as analogues, prior experiences, and perspectives and scaffolding that performance with tools and strategies that support schema development, problem definition, information searching, analogical and causal reasoning, and argumentation provides a complete cognitive apprenticeship environment.

WHAT IS AN AUTHENTIC PROBLEM?

Situated learning theories stress the importance of embedding instruction in authentic, everyday problems. As stated before, learning always occurs in some context. The assumption of this book is that by engaging students in solving more authentic problems, more authentic, socially mediated, and personally relevant kinds of learning will result. However, there have emerged two broad conceptions of authenticity: preauthentication and emergent authenticity. Preauthentication refers to analyzing activity systems and attempting to simulate an authentic problem in a learning environment. Preauthentication is what Barab and Duffy (2000) refer to as a practice field, in which students can practice learning how to function in some field, such as mathematics. The other conception of authenticity is a field of practice (Barab & Duffy, 2000) in which students are embedded in an authentic setting, allowing them to learn a skill by engaging in the activities germane to that field (Barab, Squire, & Dueber, 2000; Nicaise, Gibney, & Crane, 2000; Radinsky, Buillion, Lento, & Gomez, 2001). Fields of practice possess attributes of apprenticeships. The authenticity emerges from the practice in an authentic setting.

This book generally focuses on presenting preauthenticated problems to students as a form of cognitive apprenticeship within the normal constraints of formal education. However, virtually all of the recommended uses of cases and cognitive skills apply equally well to both kinds of problems, regardless of whether the problem to solve is preauthenticated or emergent. Whichever kind, preauthenticated or emergent, the problem should be the focus of the learning.

WHAT MODELS OF PROBLEM-SOLVING LEARNING ENVIRONMENTS EXIST?

There have been several implementations of situated learning and cognitive apprenticeships. Two of the better-known implementations include anchored instruction and goal-based scenarios.

WHAT IS ANCHORED INSTRUCTION?

Perhaps the best known and most effective implementation of situated learning is anchored instruction. Based on situated-learning theory and cognitive apprenticeships, anchored instruction embeds problems into complex and realistic scenarios, called macrocontexts. Developed by the Cognition and Technology Group at Vanderbilt (1991, 1993), anchored instruction uses high-quality video scenarios for introducing a problem and engaging learners in order to make the problems more motivating and easier to search. The video is used to present a story narrative that requires the learners to articulate the problem to be solved, rather than having the entire problem circumscribed by the instruction. All of the data needed to solve the math and science problems are embedded in the story, enabling students to make decisions about what data are important. The problems that students generate and solve are complex, often requiring more than twenty steps to solve, rather than simple story problems.

The Cognition and Technology Group at Vanderbilt designed and developed two full series of video-based problems: The Adventures of Jasper Woodbury and Scientists in Action. The Adventures of Jasper Woodbury consists of twelve video-based adventures (plus video-based analogs, extensions and teaching tips) that focus on mathematical problem finding and problem solving. Each adventure is designed from the perspective of the standards recommended by the National Council of Teachers of Mathematics. In particular, each adventure provides multiple opportunities for problem solving, reasoning, communication, and making connections to other areas such as science, social studies, literature, and history.

In the geometry series for grades 5 and up, Paige Littlefield, a Native American, is following a set of clues to find a family heirloom her grandfather left for her in a cave. As Paige searches for the cave we learn about topographic maps and concepts of geometry important for measurement. An accident occurs when Paige reaches the cave. Students must help her friend, Ryan, find the cave on a map and give directions for the Rescue Squad to get there as quickly as possible. Incorporating real-world map-reading skills with angle and linear measurement, this is a challenging episode for math and social studies.

In the series Working Smart, teenagers Jasper, Emily, and Larry compete in a problem-solving contest sponsored by a local travel agency. They set about creating mathematical "smart tools" that will allow them to solve several classes of travel-related problems efficiently and quickly in hopes of winning an all-expenses-paid trip anywhere in the USA. All three episodes help students see the power of algebra, demonstrating that a mathematical representation can be created from a whole class of problems.

Using the same set of assumptions used to design the Jasper series, the Young Scientist series provides scientific adventures for students to solve. In the Stones River Mystery, students in the field and in an electronically connected classroom have been monitoring a local river for pollution. During one sampling trip they notice that the measures they are monitoring have begun to change. The students and scientists must work together to determine where the pollution in coming from. In the Lost Letters of Lazlo Clark, a "time capsule" has been found during a renovation of the local high school. In it are letters and a map from Lazlo Clark, a local philanthropist who had donated a large tract of land to the area almost 100 years ago. Students and their science teacher set out to find some Native American petroglyphs mentioned in Clark's letters. While their initial trip is not successful it helps them understand the importance of planning to make such a trip and how much science is needed.

Anchored instruction has proven very successful in both engaging students and getting them to solve problems more complex than their teachers thought possible. The basis of their success is student ownership of the problems.

The Jasper Series of video-based story problems, on the other hand, has been shown to successfully engage students in complex mathematical problem solving and transfer (Cognition and Technology Group at Vanderbilt, 1997) in large part because of the narrative complexity and the video medium. The narrative anchor is essential to ownership and engagement in the problem solving. It is important to note that support for the Jasper series is not universal, especially in the mathematics-education community. Many educators and parents harbor divergent beliefs about what is important to learn in math.

WHAT ARE GOAL-BASED SCENARIOS?

In goal-based scenarios (GBSs), students become active participants in a scenario (as compared with anchored instruction, in which learners only observe the scenario). GBSs teach complex systems by identifying a goal to be achieved and a set of skills the student can learn and apply in the context of the system in question. They employ a "learning by doing" architecture (Schank & Cleary, 1995) in which learners are immersed in a focused, goal-oriented situation (e.g., selling Yellow Pages advertising, accommodating new business practices), required to perform authentic, real-world activities, and supported with advice in the form of stores that are indexed and accessed using case-based reasoning formulae. The situatedness of the instruction facilitates comprehension, retention, recognition of the conditions of in which learning may be applied and therefore transferred. Skills are developed through practice in an authentic environment, so the scenario must be fairly realistic, feedback continuously provided and the action-outcomes plausible. Learning is driven by acceptance of a meaningful goal. Although numerous GBSs were developed by Schank and his colleagues, no empirical research on their effectiveness has been reported.

WHERE DO YOU FIND PROBLEMS?

Problems are everywhere. They suffuse our personal and professional lives. Individuals, families, neighborhoods, communities, regions, states, and countries are faced with myriad problems that could provide a more meaningful focus for learning than memorization. Thinking about what to teach in terms of problems rather than topics can be vexing when first undertaken. Our educational systems are organized around the delivery of topics. One approach to articulating problems is to think of authentic problems that are associated with those topics. That is a challenging task for teachers, professors, and designers who think in terms of topics. The task will assess how well we understand the content that we teach. For example, rather than teaching dates and places in history, examine history through the problems that people solved throughout history. For example, how did the third-century Roman Empire control runaway inflation? How should Napoleon have planned for the Russian invasion? Should Truman have dropped the first atomic weapon on Hiroshima in order to accelerate the end of the war? How did medieval serfs sustain themselves on a daily basis? Problems are everywhere, and they are personal. Redefining instruction in terms of problems rather than topics will challenge most educators.

If you need inspiration, consult news publications. Small-town, metropolitan, and international newspapers as well as news magazines are replete with problems that could engage students in PSLEs. The local, small-town newspaper that serves our summer home is filled with ballot issues, housing problems, economic-development issues, sanitation problems, affordable-housing difficulties, and a host of other problems for which myriad economic, political, sociological, cultural, scientific, and mathematical perspectives abound. Nascent attempts at problem-based learning benefit from tackling local issues first, because of their relevance. Move from those local issues to statewide problems, and then you may be prepared to tackle any one of the hundreds of national and international problems described in news magazines. There are far more problems available than any amount of instructional time can begin to accommodate.

If you are still unable to think of any problems, then log onto the Union of International Associations (www.UIA.be). They maintain a database of over 56,000 problems. The problems vary from the very specific (e.g., nappy rash) to very global and ill defined (e.g., narco-terrorism). Most of the problems are ill structured and relatively undefined. That is, you will need to define the problem (see Chapter 15). Defining the problem may mean contextualizing the problem, assuming differ perspectives (see Chapter 13), or adding prior experiences (Chapter 12) or analogous cases (Chapter 11).

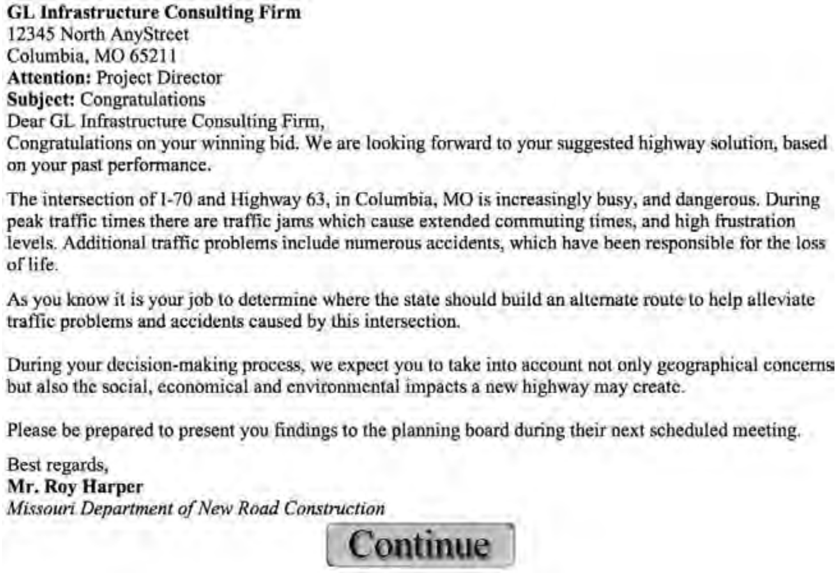
WHAT ARE THE CHARACTERISTICS OF CASES AS PROBLEMS TO SOLVE?

The success of any PSLE is largely dependent on the quality of the case as problem to solve. The case provides students with the purpose for learning, so it should be compelling. I briefly describe and exemplify the characteristics of a good case as problem to solve.

Problems to solve should present an authentic task to solve. That problem becomes the macrocontext in which students will learn. In a PSLE that we constructed to support a geography class (also described in Chapter 13), we provided a couple of problems that required students to use different maps to design solutions to complex problems In the first problem, students assumed the role of a member of a consulting firm that just won a contract to design an alternative route to bypass a poorly designed intersection (see Figure 8.1).

In the environment, we provide perspectives from business people, motorists, accident reports and also provide a variety of maps that students will use to locate the best route for an alternate intersection (see Chapter 13 for examples). Students are required to design an alternate route and to develop an argumentative report (see Chapter 20) to justify their route, making this a fairly authentic task.

Ask any preservice teacher what their primary concern is about teaching, and most will say classroom management. For an educational psychology course we designed a PSLE full of classroom-management problems. In the early problems, we scaffolded students' analysis of the case by providing a framework consisting of questions such as what was the behavioral problem, what you would do, why you would do that, and how certain you are of your answer (a metacognitive prompt; see Chapter 21). In addition to prompts, students are provided with perspectives from teachers, guidance counselors and other school personnel as well as theoretical perspectives provided by scholars (see Chapter 13 for example). In a real classroom, students would not have access to



GL Infrastructure Consulting Firm
12345 North AnyStreet
Columbia, MO 65211
Attention: Project Director
Subject: Congratulations
Dear GL Infrastructure Consulting Firm,

Congratulations on your winning bid. We are looking forward to your suggested highway solution, based on your past performance.

The intersection of I-70 and Highway 63, in Columbia, MO is increasingly busy, and dangerous. During peak traffic times there are traffic jams which cause extended commuting times, and high frustration levels. Additional traffic problems include numerous accidents, which have been responsible for the loss of life.

As you know it is your job to determine where the state should build an alternate route to help alleviate traffic problems and accidents caused by this intersection.

During your decision-making process, we expect you to take into account not only geographical concerns but also the social, economical and environmental impacts a new highway may create.

Please be prepared to present you findings to the planning board during their next scheduled meeting.

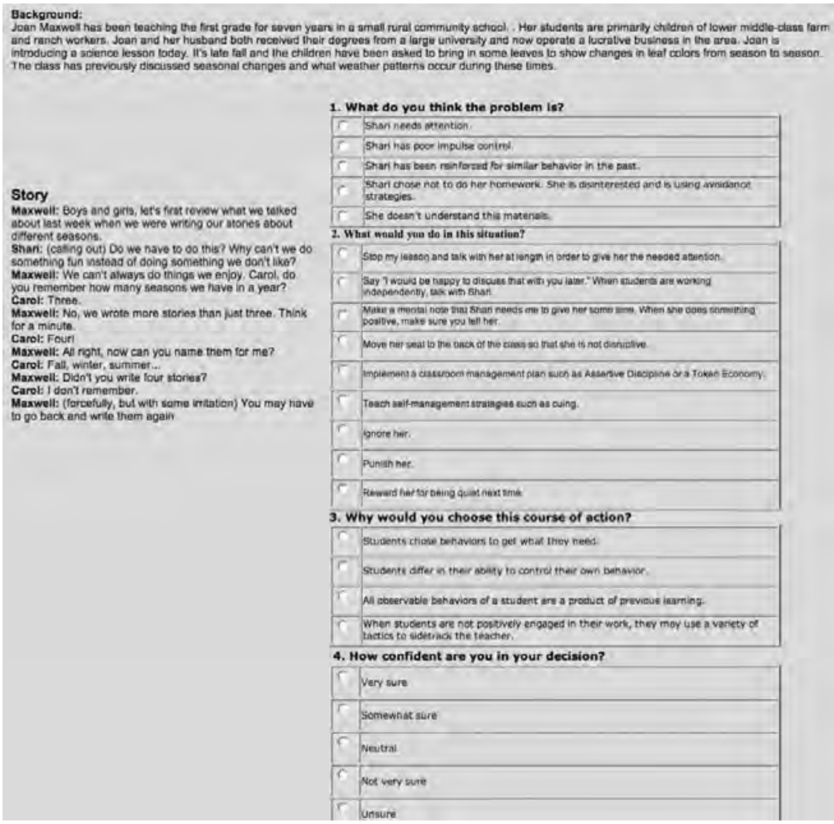
Best regards,
Mr. Roy Harper
Missouri Department of New Road Construction

Figure 8.1 Setting the problem.

such prompts. Yet the thinking that is scaffolded by those prompts helps them to solve the problem. Problems should sequence instruction from simple to complex, using a variety of scaffolds, such as the prompts in Figure 8.2. It is important to note that it is impossible to recreate a naturally occurring activity system in classrooms or online. They are emergent, not planned. So, in this environment, we simulated the classroom management diagnosis process in a pseudo-realistic environment.

Another important characteristic of cases as problems to solve is to allow for student errors and error recovery. Learning from our errors is a much more powerful experience than learning from rules.

Problems to solve are normally conveyed in the form of a story. We begin most of our environments as a story, because they are memorable, easy to understand, and engaging (see Chapter 12). In a PSLE developed for an evolutionary biology course, students solved a number



Background:
Joan Maxwell has been teaching the first grade for seven years in a small rural community school. . Her students are primarily children of lower middle-class farm and ranch workers. Joan and her husband both received their degrees from a large university and now operate a lucrative business in the area. Joan is introducing a science lesson today. It's late fall and the children have been asked to bring in some leaves to show changes in leaf colors from season to season. The class has previously discussed seasonal changes and what weather patterns occur during these times.

Story

Maxwell: Boys and girls, let's first review what we talked about last week when we were writing our stories about different seasons.
Shari: (calling out) Do we have to do this? Why can't we do something fun instead of doing something we don't like?
Maxwell: We can't always do things we enjoy. Carol, do you remember how many seasons we have in a year?
Carol: Three.
Maxwell: No, we wrote more stories than just three. Think for a minute.
Carol: Four!
Maxwell: All right, now can you name them for me?
Carol: Fall, winter, summer...
Maxwell: Didn't you write four stories?
Carol: I don't remember.
Maxwell: (forcefully, but with some irritation) You may have to go back and write them again

1. What do you think the problem is?

○ Shari needs attention.
○ Shari has poor impulse control.
○ Shari has been reinforced for similar behavior in the past.
○ Shari chose not to do her homework. She is disinterested and is using avoidance strategies.
○ She doesn't understand this materials.

2. What would you do in this situation?

○ Stop my lesson and talk with her at length in order to give her the needed attention.
○ Say "I would be happy to discuss that with you later." When students are working independently, talk with Shari.
○ Make a mental note that Shari needs me to give her some time. When she does something positive, make sure you tell her.
○ Move her seat to the back of the class so that she is not disruptive.
○ Implement a classroom management plan such as Assertive Discipline or a Token Economy.
○ Teach self-management strategies such as cuing.
○ Ignore her.
○ Punish her.
○ Reward her for being quiet next time.

3. Why would you choose this course of action?

○ Students chose behaviors to get what they need.
○ Students differ in their ability to control their own behavior.
○ All observable behaviors of a student are a product of previous learning.
○ When students are not positively engaged in their work, they may use a variety of tactics to sidetrack the teacher.

4. How confident are you in your decision?

○ Very sure
○ Somewhat sure
○ Neutral
○ Not very sure
○ Unsure

Figure 8.2 Classroom management PBLE.

of cases about the evolution of diseases. In one case (see Figure 8.3), a mother is wrestling with how aggressively to treat her child's fever. One doctor recommends a fever-reducing agent while another claims that fever is a biological adaptation, a kind of defense mechanism that should be allowed to run its course (see Figure 8.4)

Cases as problems to solve should set the problem challenge, that is, require learners to generate a solution and to justify it. In the fever problem, the mother must decide which course of treatment to pursue and ultimately justify it to herself.

Another characteristic of cases as problems to solve that was initiated by anchored instruction is the concept of embedded data design. In anchored instruction scenarios, all of the information needed to solve the problem is contained in the scenario. Applying the same principle to PSLEs, all of the information needed to solve a problem should be embedded in the environment, including a problem to solve and cases as analogues, multiple perspectives, prior experiences, and simulations

Colin is a professor at the local community college who teaches biology. He has a special interest in evolutionary biology. His wife Rachel is a stay at home mom who cares for their 4 year old son Parker. Parker started attending half day preschool three weeks ago. Two days ago, Parker began having a runny nose but no other symptoms. Overnight, Parker woke up calling out for his mommy. Parker told Rachel that he felt "yucky". Upon picking him up, Rachel noticed that he felt very warm. His temperature was 100.1° F orally. Rachel has been up since midnight holding and rocking Parker, concerned about his fever. Rachel decides to wake Colin…

"Wake up honey; I think we need to get bubby checked out….he's been running a temperature since midnight."
Rolling over and awaking from a great fishing dream, Colin states "what?"
"Parker isn't feeling good; I've been up all night with him. He's running a fever and I'm really concerned."
"Wait a minute Rachel….what's his temperature been running?"
"Well it's been about 100° F. I know you've said in the past not to give him anything for a temperature less than 102°, but it just seems to be hanging on and he feels really hot. He's been a little fussy and has wanted me to hold him all night long."
"It'll be okay….let's stop and exam this for a minute."

Colin: I really want Parker to feel better too, and I'm sorry that you've had to be up with him all night. You said that his fever's been running about 100?
Rachel: Yeah. It just keeps hanging in there…It's been running around 100 for about the last 6 hours. I'm wondering if we need to get him checked out when Dr. Bailey's office opens up. I just hate this feeling of not being able to do anything for him. I know he's got to be feeling miserable with his temperature being up. I know how I feel when I've got one…isn't there something we could do?
Colin: Well you know what the research says about fever….

Fever in Different Species

Rachel: I know, I know….but most of that research is dealing with animals and insects, not our child!
Colin: You're right…not a lot of research has been done with humans, which is understandable. But we have to consider what evidence there is and how it could apply to us…

Mechanism of Fever

Figure 8.3 Evolution of a fever case.

Here is what the traditional treatment will do ...

Child Fever: The Dr Chris 5 Cs action plan.

However ...

Randolph Nesse Interview (2/5) - Richard Dawkins

Questions

- For both treatment options (giving Parker children's Tylenol to reduce his fever vs. allowing his fever to remain untreated), provide a list of the potential costs and benefits.
- In the video interview with Dr. Randolph Nesse, he suggests that much of general medicine consists of treatments that disarm the body's natural defenses (eliminating cough, reducing fever, preventing vomiting, etc.). If these natural defenses have evolved because of their health benefits, why does it often work out just fine to treat them anyway?
- Experimental studies of various species have shown over and over again that fever can be critical for survival. In contrast, most studies with humans have shown little effect of fever suppression on the progress of disease. How can you reconcile these contrasting results?
- It has been estimated that each year in the USA there are about 1 billion cases of the common cold, and many of these infections will be accompanied by a low-grade fever. After having read some of the pros and cons of treating a fever, what do you think you will do the next time you get a cold?
- What are your suggestions for Rachel and Colin in treating Parker's fever and why?

Figure 8.4 Alternative perspectives on fever case.

to support the problem solution. This would suggest that students have no need to conduct information searches in order to find information to help solve the problem. Embedded data design yields a more controlled environment, but problems provide one of the best reasons to conduct information searches. So, what portion of necessary information is included in the PSLE and what portion students need to search for is an open question that needs to be researched. Until students develop information-searching skills to support problem solving, they will likely rely exclusively on what is provided and need help in developing those skills.

9

CASES AS WORKED EXAMPLES OF WELL-STRUCTURED PROBLEMS

Concepts (aka schemas; see Chapter 15) are the bases of human understanding and reasoning. Concepts are the mental representations that humans construct to interpret phenomena in the world. The most popular psychological conception of a concept is a schema. A schema consists of slots (placeholders) in which attributes of the concept are embedded. So, we construct schemas (concepts) based on their associations (links) with other schemas. According to Thagard (1992), concepts are predicates taking one argument (attributes). Among the most common attributes of concepts is the instance or example. That is, a concept (Chevrolet) is an instance or example of a more general concept (automobile).

Concepts are applied when we recognize an example or instance as a member of a concept ("There is a Chevrolet"). Concept categorization is the most pervasive cognitive process in everyday life (Rehder, 2003) as we access terms to describe what we are thinking or interpret what others say to us. Concepts play essential roles in human reasoning, including categorization, learning, memory, deductive inference, explanation, problem solving, generalization, analogical inference, language comprehension, and language production (Thagard, 1992). More than anything, concepts promote "cognitive economy" (Rosch, 1978). By partitioning the world into classes, concepts decrease the amount of information that we must learn, remember, communicate, and reason about. Concepts enable humans to economically store information about categories of objects, events or entities that can be used to describe and reason about every instance of the category.

Just as concepts are the basis for understanding, examples are the basis of instruction to promote that understanding. The surest way to communicate an idea is to show examples of that idea and to enable learners to induce meaning from those examples. Classical views of concept learning (Gagné, 1968; Merrill, 1983) assume that explication of the critical attributes illustrated by those examples is essential to instruction. However, constructing concepts (schemas) for problems necessitates a more actional view of concepts where conceptualizing is a kind of doing (Gilbert & Watts, 1983). They claimed that concepts are active, constructive, and intentional. Concepts are ways of organizing our experiences. Learning to solve different kinds of problems is experiential. According to Kelley's (1973) personal construct theory, conceptual development can be seen as continuous, active, creative process of differentiation and integration. So, constructing concepts (schemas) for different kinds of problems (the goal of Chapter 15) relies on associating examples of problems with their constituent concepts based on the experiences of solving problems. Because concepts change meaning over time, in different contexts, and for different purposes, concepts for problems (kinds of problems; see Chapter 1) will also change with additional problem-solving experience. For an explication of theories of concept learning, see Jonassen (2006b).

Traditional models of concept learning (Merrill, 1983) recommend that both positive and negative examples (also known as nonexamples) of concepts be presented during instruction. Positive examples of concepts enhance concept generalization, while negative examples enhance discrimination. Concept learning is assessed by presenting new instances to learners and requiring them to determine whether the instance is or is not a member of the concept class being assessed. Although I have argued elsewhere that this model of concept learning does not capture the complexities of concept learning (Jonassen, 2006b), it is interesting that these instructional strategies have not been tested with regard to worked examples, the concept introduced in this chapter.

WHAT ARE WORKED EXAMPLES?

How are cases as examples used in problem-solving instruction? The most common form of cases as examples in problem solving is the worked example. When learning to solve problems, cases in the form of worked examples may be provided as a primary form of instruction. In a worked example, the teacher or professor models the process for solving problems (usually a story problem at the end of textbook chapters). Worked examples typically include the problem statement and a procedure for solving the problem for showing how other problems may be solved (Atkinson, Derry, Renkl, & Wortham, 2000; see Figure 9.1).

The purpose of worked examples is to help learners to construct schemas for the worked example that may then be generalized or transferred to new problems. Learners are expected to induce a schema from the example, store the schema in memory, and later analogically transfer it when a solving a new problem (Gick & Holyoak, 1983). This method of problem solution too often emphasizes the quantitative representation of the problem (solving equations; see Chapter 2) to the exclusion of conceptual understanding, so the schemas that students construct are process schemas that are bereft of conceptual associations.

A substantial corpus of research has shown that worked examples of problem solutions that precede student practice facilitates learning to solve some kinds of problems by helping learners to construct problem-solving schemas (Cooper & Sweller, 1987; Sweller & Cooper, 1985). Sweller and Cooper (1985) found that the worked-example approach was significantly less time consuming than the conventional problem-solving method. Furthermore, learners required significantly less time to solve similar problems and made significantly fewer errors than did their counterparts. They concluded that the use of worked examples may redirect attention away from the problem goal and toward problem-state configurations and their associated moves. Additional research has shown that worked examples are more effective when multiple examples per problem type are used in multiple

PROBLEM: A car is driving from Kansas City to St. Louis, a distance of 250 miles. At 50 miles per hour, how long will it take to travel between the two cities.

SOLUTION:
STEP 1:
Total distance between cities: 250 miles
Rate (velocity) of travel: 50 miles per hour

STEP 2:
If distance = rate * time
Then time = distance/rate

STEP 3:
Distance of 250 miles divided by 50 miles per hour equals 5 hours.

ANSWER: The time required to drive from Kansas City to St. Louis is 5 hours.

Figure 9.1 Worked example of simple problem.

forms that feature structural components of the problem, including sub-goals (Atkinson et al., 2000). Another way that worked examples are improved is the explanation of sub-goals in the problem. Rather than remembering a set of steps for solving problems, Catrambone (1994, 1996) claims that it is important that worked examples should explicitly describe the sub-goals that are important to the knowledge domain that are embedded in the steps. When individual steps in a problem solution change but the overall procedure remains the same, students often fail to transfer their skills when they are not aware of the sub-goals required to solve the problem. In series of experiments, he showed that students who studied solutions emphasizing sub-goals were more likely to solve new problems requiring sub-goals.

A newer issue that has been investigated relative to worked examples is the role of self-explanations. Mwangi and Sweller asked third graders to self-reflect by asking them to "to pretend they were explaining the solution to another child who did not know how to solve the problem" (1998, p. 180). Otherwise known as a teachback, this method is intended to support schema development by having problem solvers reflect on what they have done and attempt to integrate it with what they already know. Although Mwangi and Sweller found no benefit from self-explanations, Renkl, Stark, Gruber, and Mandl (1998) found that self-explanations improved near transfer and far transfer of problem solving. Understandably, the quality of the self-explanation best predicted the ability to transfer. Self-explanations occur naturally among learners. Chi, Bassock, Lewis, Reiman, and Glaser (1989) found that higher achieving students naturally generate self-explanations by expanding their solutions to other problems and monitoring their own understanding and misunderstanding. Those self-explanations come from knowledge acquired while trying to instantiate ideas while reading the text and also from generalizing those example statements (Chi & Van Lehn, 1991). Self-explanations require active and intentional attempts to make sense out of what is being studied.

In an extensive review of the research on worked examples, Atkinson et al. (2000) provide a number of prescriptions about how to use and present worked examples. They recommend the following:

- Use multiple worked examples for each type of problem being learned.
- Use multiple forms (situations) for each type of problem being learned.
- Pair examples of each kind of problem.

- Present the worked example using different modalities (aural, visual, etc.) for each example.
- Clarify the sub-goal structure of the problem or each example.
- Encourage the use of self-explanations during and after solution.

WHY USE WORKED EXAMPLES?

When faced with a problem, learners usually attempt to retrieve everything that they know about solving that kind of problem. Whatever knowledge they retrieve is transferred, according to information-processing models of cognition, into working memory. Working memory is a temporary memory buffer that holds information for short periods of time. The capacity of working memory is limited, usually to two or three items that are being manipulated, compared, or otherwise processed (Sweller, van Merrienboer, & Paas, 1998). So, when learners retrieve what they know about solving a problem plus having to juggle elements of the current problem being solved, it is easy for working memory to become overloaded. Information about the problem or the solution procedures falls out and has to be re-accessed, bumping something else out of working memory. Demands on working memory make problem solving more difficult.

In order to ameliorate the limitations of working memory, researchers have distinguished three different kinds of cognitive load (Chandler & Sweller, 1991; Sweller, 1988). Intrinsic cognitive load refers to the demands on working memory that are inherent in the task or the content to be learned. The more interactive elements involved in the learning task, the greater will be the intrinsic cognitive load. Germane cognitive load refers to the load required to learn the content. Learning, as defined by Sweller and colleagues, involves cognitive processes such as interpreting, exemplifying, classifying, inferring, differentiating, and organizing (Mayer, 2002). The more of these processes that are engaged by learning new material, the greater will be the germane cognitive load. Extrinsic cognitive load, the most heavily researched, refers to the load that is imposed by the instructional materials. The demands of learning materials that do not directly contribute to learning define extrinsic cognitive load. According to cognitive load theory, these types of load are additive.

An important goal of instruction, according to cognitive load theory, is to reduce the amount of cognitive load demanded of learners. Most efforts have focused on reducing extrinsic cognitive load that does not contribute to learning. One way to reduce demand on working memory is to retrieve better organized and more integrated memories about the problem being solved. A common conception of those memories is the schema (see Chapter 15). A schema for some phenomenon consists of all of the attributes that are associated with that idea. Say a word and then think as quickly as possible of the first ten things that come to your mind when you say that word. Those associations form a rough model of a schema. A schema for a problem consists of the kind of problem it is, the structural elements of the problem (e.g., acceleration, distance, and velocity in a physics problem), situations in which such problems occur (e.g., inclined planes, automobiles, etc.), and the processing operations required to solve that problem. When schemas are well organized and integrated, they can be brought into working memory as a whole chunk, thereby placing lower demands on working memory. The development of problem schemas can be supported by explicitly modeling the structure of the problem during the worked example and by practicing solving particular kinds of problems. With extensive practice and reflection, schemas for different kinds of problems become automated. This is how experts become very efficient problem solvers. When they see a problem, they immediately classify its type and execute their schema that includes conceptual knowledge, processing operations, fix-up strategies, and so on. So, rather than having to perform numerous steps in analyzing and setting up the problem, the expert fires a schema that contains necessary knowledge of operations.

Cognitive-load researchers prefer using worked examples to reduce cognitive load. While conventional approaches to problem-solving instruction present basic principles, usually in an abstract way, followed by extensive practice on problems, worked examples include the problem statement and a procedure for solving the problem (Figure 9.1) for the purpose of showing how other problems may be solved. The traditional approach to solving problems is means–ends, where students identify the goal and work backward to figure what needs to be done next. This approach imposes a heavier cognitive load on working memory because learners have to pay attention to differences in problem states rather than to each state and its associated moves. Worked examples reduce that cognitive load and improve performance unless the worked examples require learners to mentally integrate multiple sources of information (Sweller, 1988; Ward & Sweller, 1990).

Worked examples and cognitive-load theory are not universally embraced. Ton de Jong (2010) has articulated a number of concerns about cognitive-load theory. He argues that it is virtually impossible to differentiate between the kinds of cognitive load because they are all so interactive. Intrinsic and germane cognitive load are especially problematic, particularly when learning to solve complex problems. In complex problems, the content requires greater cognitive load, but so do the processes for solving complex problems. He also questions whether the different types of load are simply additive. One of the most common misconceptions of cognitive-load theory results in the conflation of cognitive load and cognitive effort. While load refers to working-memory demands, doesn't every process involve working memory? Finally, from a research perspective, measuring cognitive load is very inexact, most often accomplished with self-report measures. Although demands on working memory are an important variable in learning, problem solving, especially with complex and ill-structured problems, is much more multi-faceted.

WHAT ARE THE LIMITATIONS OF WORKED EXAMPLES?

Despite the intended cognitive outcomes from worked examples, a number of difficulties in solving problems consistently occur:

- deficient schemas;
- generalization vs. discrimination;
- mapping the incorrect problem schema to the target problem, and the over-reliance on single analogues, and the lack of conceptual development;
- the difficulties associated with ill-structured problems.

What Are Deficient Schemas?

Worked examples, like most approaches to problem-solving instruction, assume that the learners induce or construct a schema for particular kinds of problems following demonstrations of the process. When shown only how to procedurally solve problems in worked examples, learners are left with deficient problem schemas. In order to learn how to solve different problems, learners access their problem schema in order to classify the problem (see Chapter 2 and 15; Chi, Feltovich, & Glaser, 1983). The most successful methods for teaching problem solving support student construction of problem schemas (Taconis, Fergusson-Hessler, & Broekkamp, 2001), because it is the quality of students' conceptual models that most influences the ease and accuracy with which problems can be solved (Hayes & Simon, 1976). Complete problem schemas include not only the process for solving the problem but also the concepts that are normally included in each type of problem, their structural relationships, and situational characteristics. When students learn only the process for solving a problem, they tend to mimic that process without understanding what kind of problem it is. That is, their problem schema is a process schema. To solve problems consistently, learners must demonstrate conceptual understanding of the problems by constructing problem schemas for each kind (e.g., conservation of momentum, angular motion, or kinematics in physics) or by examining problems for their structural characteristics (Reusser, 1993). After accessing an appropriate schema, only then should students apply the procedure.

What happens when students learn only processes? They tend to apply only those examples that are similar to the target problem. Mapping examples to problems is affected by the similarity of objects between the examples and problems being solved, especially story lines and object correspondences (whether similar objects filled similar roles) (Ross, 1987, 1989a). Learners often fail to recall or reuse examples appropriately because their retrieval is based on a comparison of the surface features of the examples with the target problem, not their structural features. When the target problems emphasize structural features that are shared with the example, generalization improves (Catrambone & Holyoak, 1989; Reed, 1987).

Are Generalization and Discrimination Required?

Learners are expected to induce schemas from the examples, store the schemas in memory, and later analogically transfer to them when solving problems (Gick & Holyoak, 1983). The transfer is a form of knowledge generalization. Generalization from problem-solving examples may automatically occur in limited ways (Catrambone & Holyoak, 1983); however, knowledge generalization is not a natural consequence of reasoning by analogy (Didierjean, 2003). Learners sometimes adapt highly specific, contextualized knowledge from analysis of examples without engaging in the reasoning-by-analogy process that leads to generalization. Attracting attention to the similarity between problems improves generalization during problem solving (Didierjean, 2003). However, learning the differences between problem types also requires discrimination. As a result, when asked to compare problems or to transfer solution methods to more contextually varied problems, students typically generalize problem solutions based on surface-level similarities among problems (Chi et al., 1981; Dufresne, Gerace, Hardiman, & Mestre, 1992; Hardiman, Dufresne, & Mestre, 1989; Schoenfeld & Herrmann, 1982). When asked to recall problems, students recall relevant examples, especially when the two problems differ in surface features, because people focus on surface features (Gentner, 1989; Medin & Ross, 1989). Loewenstein, Thompson, and Gentner

(1999) showed minimal transfer from a single example. Unfortunately, transfer from a single problem is insufficient for schema induction.

What Are the Dangers of Single Analogues?

In order to teach students how to solve problems in most classes, instructors demonstrate how to solve a problem and then ask learners to apply the demonstrated method to solve a new transfer problem. Transferring learning from a single example to a new problem requires that learners induce a schema for that kind of problem from that single example and then apply that schema to a new, contextually varied problem (see Chapter 15 for more detail on problem schemas). This single-example approach to teaching problem solving usually results in students attempting to mimic the process for solving the problem while ignoring the semantic, structural characteristics of the problem. Another issue in schema induction and analogical transfer is the number of worked examples that are required for schema induction. Ahn, Brewer, and Mooney (1992) showed that learners can build a schema from analyzing a single example. However, Catrambone and Holyoak (1989) showed that transfer was enhanced when more examples (three rather than two) were shown. The obvious solution to this limitation is to use multiple examples before requiring students to solve their own problems, a feature that was highlighted by Atkinson et al. (2000).

Do Worked Examples Apply to Ill-Structured Problems?

The research on worked examples and cognitive load has been conducted with well-structured mathematics and science problems that possess correct solutions, accepted solution methods, and accepted criteria for assessing the solution. Even with well-structured problems, research results have been somewhat equivocal, given the absence of assessments of conceptual understanding of problems. Can worked examples be effectively applied to ill-structured problems? Although some researchers are beginning to address ill-structured problems, no empirical research exists yet to answer this question. How can you demonstrate a process for solving a problem that does not have a known process? How does the learner know which concepts and which relationships to test? How do learners know whether solutions are appropriate? Were worked examples applied to ill-structured problems, they would necessarily increase intrinsic and germane cognitive load to an unacceptable level.

WHAT SHOULD WORKED EXAMPLES INCLUDE?

I believe that worked examples can effectively enhance learning to solve problems if they present adequate conceptual instruction as well as procedural. Worked examples should present multiple examples in multiple modalities for each kind of problem, emphasize the conceptual structure of the problem, vary formats within problem types, and signal the deep structure of the problem (Atkinson et al., 2000). Worked examples should explicitly describe the sub-goals that are important to the knowledge domain that are embedded in the steps. Students who studied solutions emphasizing sub-goals were more likely to solve new problems requiring sub-goals Catrambone (1994, 1996).

In addition to the characteristics of good worked examples provided by Atkinson et al. (2000), I suggest that worked examples also include the following:

- Identify all of the elements in the problem conceptually (e.g., in work–energy problems, identify the initial and potential energy, etc.).
- Identify the relationships among those problem elements and the changes in those elements as the problem is solved and why those changes occur.
- Compare each problem with similar problems (see Chapters 11 and 16).
- Contrast each problem type with different problem types (e.g., how are work–energy problems different from conservation problems?).
- Think aloud (Ericsson & Simon, 1993) in which the teacher explains why and how the process is used as well as metacognitive reflection (see Chapter 21).

The only problem with these recommendations is that they will necessarily increase cognitive load. Conceptually, there exists a strong correlation between conceptual understanding and cognitive load. Conceptual understanding requires mental effort. That effort is worth it. If students construct more robust schemas that include conceptual as well as process information, applying those schemas will require less cognitive load, which should be an important goal of problem-solving instruction.

10

CASE STUDIES: EXAMPLES OF ILL-STRUCTURED PROBLEMS

Note: If you search for literature on case studies, be aware that there are two distinct yet somewhat related meanings for the term. In this chapter, I describe case studies as an instructional methodology, where a (usually) written description of a real-world practice situation is provided to students to analyze, discuss, and learn from. Case studies also represent a qualitative research method that typically involves a long-term, in-depth investigation of a single event, practice, or situation. Case studies include examining events, collecting data, analyzing information, and reporting the results. The purpose of case studies is to provide a rich description of some practice. While there is nothing to prevent research case studies from being used as classroom case studies, these kinds of case studies are seldom combined.

WHAT ARE CASE STUDIES?

The most common application of case-based learning is the case study. In case studies, students study an account (usually narratives from one to fifty pages) of a problem that was previously experienced. Frequently guided by discussion questions, students analyze the problem and the information provided in support of the problem and discuss the case from the perspective of the central character. This analysis is usually ex post facto. In most case studies, students are not responsible for solving the problems, only for analyzing how others solved the problems. The goals of the case-study method are to embed learning in authentic contexts that requires students to apply knowledge rather than to acquire it.

As indicated in the Introduction to Part II (pp. 149–151) of this book, case studies provide examples of ill-structured problems that can be used to help learners to solve ill-structured problems (Chapter 8). In the previous chapter, I described how worked examples function as examples of well-structured problems that may help students learn to solve problems.

Case studies, as described in this chapter, may play another important role for students and teachers. They provide a medium for easing into problem-solving learning. Adopting problem-based learning (see Chapter 8) requires a substantial commitment to innovation that many teachers and professors are unwilling to make. However, teachers and professors who want to make their instruction more meaningful and are interested in problem-solving outcomes may want to begin with case studies. Be aware that even case studies require new instructional methods, as will be shown later in this chapter.

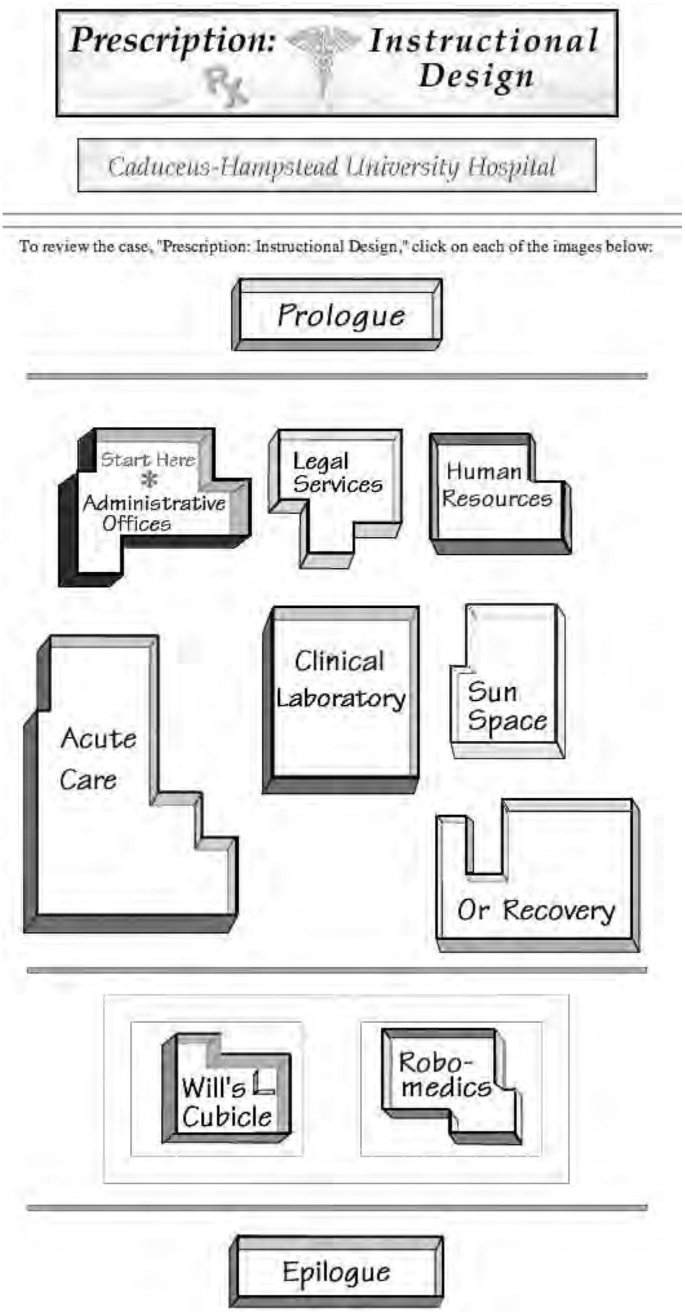
The use of case studies in education began in 1870 at the Harvard Law School, promoted by a dissatisfaction with the existing method of legal education and the epistemological congruity between the law and learning (both case-based) (Williams, 1992). That is, laws often derive from cases (case law) and are certainly mediated by cases (trials). Following legal education, case studies began being used at Harvard and elsewhere in medical and business education. Although the use of case studies in teaching began in professional schools, such as law and medicine, they have been adopted widely in many disciplines. Common examples of the case-study method include the Harvard business cases (Barnes, Christiansen, & Moore, 1994) and case studies in teacher education (Shulman, 1992; Sudzina, 1999). Although the most common case studies are in business (e.g., Harvard business cases), there exist thousands of casebooks including case studies in nearly every discipline (see Table 10.1 for a brief list of selected casebooks that show the diversity of topics). Additionally, there are organizations and societies dedicated to the case method of instruction, including European Case Clearing House (www.ecch.com), which collects and makes available business-management cases from numerous universities, Clearinghouse for Special Education Teaching Cases (http://cases.coedu.usf.edu), and many others. Although you may choose to construct your own case studies (a skill briefly addressed in this chapter), it is likely that you can find existing case studies for use in your classrooms.

Increasingly, case studies are being provided via the Internet. For example, in instructional design, many case studies have been developed at the University of Virginia (http://curry.edschool.virginia.edu/go/

Table 10.1
Selected casebooks in diverse disciplines

Case studies for stormwater management on compacted, contaminated soils in dense urban areas
Case studies for teacher decision making
Case studies for Zimbabwe, Botswana, Mauritius, and Thailand
Case studies illustrating environmental practices in mining and metallurgical processes
Case studies in atomic collision physics
Case studies in cardiovascular critical care
Case studies in childhood emotional disabilities
Case studies in constructivist teaching
Case studies in counseling and psychotherapy
Case studies in ecotourism
Case studies in equal pay for women
Case studies in left and right hemispheric functioning
Case studies in materials chemistry mixed valency magnetism and superconductivity
Case studies in pediatric surgery
Case studies in population policy in Malaysia
Case studies in public-health ethics
Case studies in shopping-center development and operation
Case studies in solvation of bioactive molecules amiloride, a sodium channel blocker, and beta cyclodextrin, an enzyme mimic
Case studies in the psychopathology of crime
Case studies of corrosion of mixed waste and transuranic waste drums
Case studies of different types of foreign direct investment processes in Finnish firms
Case studies of Midwestern thundersnow events
Case studies of rural schools implementing comprehensive school reform
Case studies of salvage logging and its ecological impacts
Case studies prosecutions of Curandeiros and Saludadores in seventeenth- and eighteenth-century Portugal

ITcases). Disseminating case studies via the World Wide Web has a number of advantages. By making the cases random access, web cases suggest real-world complexities through hyperlinking and the use of multimedia can represent simulated authentic cases in a variety of media (Kovalchick, Hrabe, Julian, & Kinzie, 2003). Web cases also enable cases to be structured and accessed in a variety of ways. For example, the primary interface for one of the Virginia cases (see Figure 10.1) provides a floor plan of a hospital in which the case problem exists.



To review the case, "Prescription: Instructional Design," click on each of the images below:

Figure 10.1 Interface for web case study. With permission from Mable Kinzie, University of Virginia.

WHAT ARE THE CHARACTERISTICS OF GOOD CASE STUDIES?

"A case is a description of an actual situation, commonly involving a decision, a challenge, an opportunity, a problem, or an issue faced by a person or persons in an organization. The case requires the reader to step figuratively into the position of a particular decision maker" (Herreid, 2007, p. 50). He goes on to suggest characteristics of good cases:

- relevant to learners;
- real: no fabrications, no fantasy;
- has a clear and consistent structure;
- focuses on interest-arousing issues;
- set within the past five years;
- creates empathy with central characters;
- has pedagogic utility, i.e. addresses relevant learning outcomes;
- contains conflict or controversial issue;
- forces decisions, i.e. includes a problem to solve.

First and foremost, case studies are normally conveyed in the form of stories, because stories are engaging, relevant, and easily comprehensible (see Chapter 12 for more detail on the power of stories). As described in Chapter 3, when information is conveyed to people in a random manner, they are likely to construct a story out of the evidence in order to make sense of it, and when information is conveyed in the form of a story, it is more effective. Although Herreid (2007) insists on reality, stories can be fabricated so that they seem real to the reader.

The power of case studies is the ability and willingness of the case reader to identify with and create empathy with the protagonist in the case story. As students in training, case studies should be interesting to them. In order to make cases more interesting, according to Herreid (2007), they should be contemporary controversies that force the student to make decisions on order to solve discipline relevant problems.

"Cases are verbal representations of reality that put the reader in the role of a participant in a situation" (Ellet, 2007, p. 13). As a substitute for direct experience, cases must have:

- significant discipline-relevant learning issue that orients the case;
- sufficient information in the case on which to base conclusions;
- no stated conclusions, requiring learner to generate conclusion.

According to Ellet, cases may also present:

- information that includes irrelevancies, dead ends, biased, or limited testimony that the learners must sort through;
- information unstated in the case that must be inferred from the situation.

In order to manifest these characteristics, cases are most often presented in the form of stories. As shown in Chapter 3, relating evidence in the form of stories is an important strategy making sense of information. Williams (1992) asks a number of questions that easily demarcate case-based from traditional instruction, such as:

- Does the instruction begin with a problem to be solved?
- Does the teacher model how to solve problems in the content of the presented problem?
- Do students actively engage in solving the problem? Do students and teacher assess how well learning is progressing?
- Are the problems authentic, like those solved by practitioners?
- Are the problems realistically complex?

To these, I would add:

- Do cases vary in the sophistication of the domain knowledge they require, because novice-level case problems should be different from journeyman or expert-level ones.
- Are the cases not over-scaffolded, with too many prompts or suggestions about how to proceed?

What makes cases so effective? Hutchings (1993) argues that case studies are effective because they are authentic, based on real-life scenarios. They are also effective because they are comprised of concrete details, conveyed in narrative form, and are open to interpretation. What makes case studies so effective is the constructive and generative thinking that they engender among students. Rather than attempting to replicate the teacher's thinking on an examination, students are required to construct their own interpretations of the cases, what Christensen (1991) refers to as "education for judgment."

HOW DO YOU TEACH WITH CASE STUDIES?

There exist a number of methods for teaching with case studies. Case studies may be used as individual assignments in the form of a thesis, term paper, directed case study, or a paper review (Mauffette-Leenders, Erskine, & Leenders, 1997). Conversely, instructors may lecture about case studies by telling stories or even arranging theatricals. However, the most common use of case studies is to foster discussions where students analyze and discuss the case. Case discussion often creates a sense of community among the participants (Hutchings, 1993). Those discussions may consist of Socratic dialogues where the instructor probes students' understanding of the case. Discussions may also take the form of a symposium, a trial, a debate, or a public hearing among alternative perspectives. While some instructors advocate for larger discussion groups of up to fifty or sixty, other instructors prefer small group discussions where students may engage in role playing, promotional presentations, poster presentations, team problem solving, or problem-based learning (Mauffette-Leenders et al., 1997). Being a discussion leader is a complex role, in which the teacher forms a partnership with students in order to form a learning community (Christensen, 1991). Being a discussion leader requires dual competency: the ability to manage content and teaching process.

How do students go about analyzing a case study? According to Ellet (2007), readers must be able to:

- construct conclusions about the problem from information presented in the text;
- filter out irrelevant or unimportant information presented in the case;
- infer information that is important to the case solution but is missing in the case;
- integrate evidence from case into a conclusion and construct a argument for the solution (see Chapter 20 on argumentation).

In order to analyze a case study, learners must be able to adopt the point of view of the protagonist (the main character in the case). Using that perspective, learners must be able to:

1. Analyze the situation in which the problem occurs (what is context) for important information.
2. Generate questions that need to be answered before generating solutions (see Chapter 18 for a description of the importance on self-generated questions).
3. Generate hypotheses about the nature of the problem.
4. Collect evidence to supporting that hypothesis.
5. Generate possible alternative hypotheses (that is, generate possible counterarguments and rebuttals against them (see Chapter 20 on argumentation).

(Ellet, 2007)

In order to engage students in case discussions, the teachers should have some sort of plan. Mauffette-Leenders et al. (1997) recommend that a normal case discussion follow a decision-making model, including the acts:

1. Define the issue.
2. Analyze the case focusing on causes and effects (see Chapter 17) as well as constraints and opportunities.
3. Generate alternative solutions.
4. Select decision criteria.
5. Analyze and evaluate alternatives.
6. Select preferred alternative.
7. Develop an implementation plan.

This discussion model is based on a normative theory of decision making (see Chapter 3). You may want to attempt a more naturalistic approach to leading case discussions.

HOW EFFECTIVE ARE CASE STUDIES?

Case studies have been used as an alternative to didactic instruction by a number of educational reformers, especially in higher education. Case studies are most prevalent in legal, business, health, science, and teacher education, where they have been used to develop real-world problem-solving skills. However, many educators continue to have concerns about the benefits of case studies because there has been little empirical research on the effects of case studies on student learning (McNaughton, Hall, & Maccini, 2001; Yadav, Lundeberg, DeSchryver, Dirkin, Schiller, Maier, et al., 2007).

Research has revealed that case studies are more effective than or equivalent to didactic instruction (Chaplin, 2009; Fisher & Kuther, 1997; Lauver, West, Campbell, Herrold, & Wood, 2009; Mayo, 2002, 2004; Schrader, Leu, Kinzer, Ataya, Teale, Labbo, et al., 2003). For instance, Mayo (2002, 2004) found that undergraduate students who analyzed and discussed cases better understood psychological theories than students who received lecture-based instruction. Chaplin (2009) found that students who studied cases in an introductory biology course significantly improved their abilities to apply theories and to analyze problem situations, whereas students in a lecture-based course did not. Further, Fisher and Kuther (1997) showed that undergraduate students who critically evaluated cases including research-ethics issues improved their problem-solving performance on ethical case problems. By contrast, didactic instruction on research ethics was not effective in improving students' ethical problem-solving performance.

In addition to learning effectiveness, students perceive that case studies are beneficial for their learning. In surveys and interviews, students frequently stated that case studies helped to reflect their misconceptions (Abell, Bryan, & Anderson, 1998), make field experiences meaningful (Baker, 2009), and connect theory with practice (Carlson & Schodt, 1995). Case discussion was perceived to be helpful because students could recognize multiple perspectives on a case and critically examine them (Barnett, 1998; Carlson & Schodt, 1995; Mayo, 2002). In addition, many students thought that case studies were more valuable and effective than traditional didactic instruction (Hayward & Cairns, 2001).

In some research, case studies have not always been more effective than didactic instruction. Lauver et al. (2009) compared case studies with lectures in terms of objective test scores in two nursing courses. The effect of case studies on test scores was not significantly different from that of lectures. In addition, Schrader et al. (2003) developed a web-based learning environment for case studies in which preservice teachers analyzed videos of reading instruction through navigating multiple resources including student and parent information, contextual information about a school, lesson plans, and teacher interviews. However, they did not find a significant effect of case studies in preservice teachers' understanding of effective reading instruction and their confidence of teaching when compared to a traditional course without case studies.

The limited effect of case studies may be related to inappropriate assessment methods. The previous research showing significant effects of case studies assessed learning outcomes with higher-order tasks requiring students to apply theories to problem situations and justify their decisions (Fisher & Kuther, 1997; Mayo, 2002). In contrast, the objective tests measuring factual knowledge and comprehension seem not to be sufficient in measuring the effects of case studies, whose benefits are associated with higher-order thinking (Chaplin, 2009). Unsurprisingly, if assessment is inconsistent with the purpose of case studies, researchers may not find a significant effect of case studies.

Some research has examined the role of learning styles on case use and efficacy. Hughes, Packard, and Pearson (2000) found that students had different levels of motivation when using cases for developing their arguments. The researchers categorized students as investors, compliers, and resisters. The different perceptions on case studies between students have been investigated in terms of learning styles (Choi, Lee, & Jung, 2008). Choi et al. found close relationships between students' learning styles and their perceptions on case studies. Students enrolled in a dental school analyzed video cases showing how expert doctors make decisions during surgery. The researchers found that students with sensing, sequential, and reflective learning styles tended to perceive the multimedia case study as more a meaningful learning experience than students with intuitive, global, and active learning styles.

In conclusion, case studies are superior to didactic instruction in terms of the higher-order thinking required to solve real-world problems rather than factual knowledge and comprehension. When instructors apply case studies, they must consider the purpose of case studies and align assessment methods with the purposes. In addition, researchers and instructors should pay more attention on individual differences to enhance the effect of case studies.

The use of case studies to support learning how to solve ill-structured problems in PSLEs has not been researched. Conceptually, this role makes sense and deserves to be researched.

11

CASES AS ANALOGIES

In Chapter 8, I described how students work on solving cases as problems. In order to help them to learn to solve those problems, teachers, professors, and designers may support student efforts with cases as worked examples (Chapter 9), case studies (Chapter 10), cases as analogies (this chapter), cases as prior experiences (Chapter 12), cases as alternative perspectives (Chapter 13), and cases as simulations (Chapter 14).

This chapter describes how providing analogous problems during instruction will enhance schema induction for the type of problem being studied, but first, I provide a brief introduction to analogies. The use of analogies to help communicate ideas has a rich tradition in instruction. Although many researchers and scholars have detailed the importance of analogies in instruction, one of the major proponents has been Shawn Glynn and his colleagues (Glynn, 1989, 1995; Glynn, Taasoobshirazi, & Fowler, 2007; Paris & Glynn, 2004). They claim, from a cognitive, not linguistic perspective, that an analogy is the process of transferring (mapping) information from a particular subject (source) to another particular subject (target). Inferring analogies helps learners to understand a new idea by comparing its attributes to the attributes of an existing, better-understood idea. Analogies are based on the similarity of attributes and the similarity of the relationships among those attributes. Glynn often describes the use of analogies for communicating the concept of a biological cell. In one analogy, he describes a cell being like a factory. The plasma membrane is like a security guard at the door protecting the contents of the cell. The nucleus is like the control center regulating the functions of the cell. The mitochondria are like a power generator fueling the cell. The ribosomes are like the production machines in a factory. An analogy is useful only if the learners have constructed a well-developed schema for the analogy. If students are unfamiliar with the characteristics of a factory, then the analogy requires more effort and likely will result in confusion. So, the teacher would have to use a more familiar analogy, such as a house. The membrane is like the walls of a house. The nucleus is like parents controlling the activities if the house. The mitochondria are like the dining room where food is consumed, and the ribosomes are like the kitchen where the food is produced.

An analogy is also useful only if the relationships are meaningful and consistent. Analogies are coherent if there is structural consistency, semantic similarity, and consistency of purpose (Holyoak & Thagard, 1997). Analogies that are isomorphic are maximally consistent. They are similar if the source and target share similar elements and relations, and they share purpose if they are oriented by the same task at hand. A very common analogy for communicating the idea of electric current is water flowing through a pipe. Although this analogy provides a rich referent for understanding an abstract idea such as electricity, according to physicists, it also conveys misconceptions about the nature of electricity. Therefore, when using analogies, it is important to generate and provide multiple analogies. In Chapter 13, Rand Spiro argues that overreliance on single analogies results in severely restricted understanding of ideas. How many analogies to provide depends on the abilities of the learners and the difficulty of the ideas being communicated.

Analogies represent one of the most essential ideas of cognitive psychology: in order to learn, it is necessary to relate new ideas to something that the learners already know. Inferring an analogy requires comparison of two seemingly unrelated ideas. In order to comprehend an analogy, learners must infer a relationship between the source and target using induction (inferring a relationship from examples), deduction (applying a general relationship to examples, or abduction (hypothesizing a relationship).

In order to teach students using analogies, Glynn recommends the following process:

1. Introduce target concept to students.
2. Remind students of what they know about analogy.
3. Identify relevant features of target and analogy.
4. Connect (map) similar features of target and analogy.
5. Indicate where analogy breaks down.
6. Draw conclusions about target.

HOW DO ANALOGIES SUPPORT PROBLEM SOLVING?

The focus of instructional analogies has been on their use for teaching new concepts. In this chapter, I focus on the use of analogies for teaching students concepts of problems, that is, problem schemas (see Chapter 15). Chapter 9 described how to use cases as examples (worked examples) to help student to learn how to solve problems. Although students are expected to construct a schema (Chapter 15) for the problem by examining the worked example, students usually construct only a process schema for the set of operations required to solve the problem but miss the underlying structure of the problem. When learners examine worked examples that illustrate certain rules and then apply lessons learned from that example to solving a new problem, they tend to apply only those examples that are most similar to the target problem. Mapping examples to problems is affected by the similarity of objects between the examples and problems being solved, especially story lines and object correspondences (i.e. whether similar objects filled similar roles) (Ross, 1984, 1987, 1989a). That is, learners often fail to recall or reuse examples appropriately because their retrieval is based on a comparison of the surface features of the examples with the target problem, not their structural features.

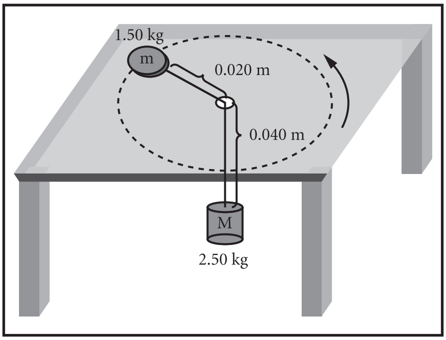
In order to emphasize the structural attributes of different kinds of problems, instruction about different kinds of problems should be supported with analogous problems. Analogies between problems involve the mapping of the patterns of relationships contained in the source problem to the target problem. When using problems as analogies, the target problem is the problem to be solved. Structurally similar analogous problems are presented to learners to compare and contrast for their structural alignment. When the target problems emphasize structural features that are shared with the source problem, generalization about the kind of problem improves (Catrambone & Holyoak, 1989; Reed, Ackinclose, & Voss, 1990). The process is known as analogical encoding and is more completely described in Chapter 16. The process involves mapping the analogy to the problem to be solved which requires emphasizing the structure of the analogy to the structure of the problem independent of the surface objects in either. Even though analogous problems may have different surface features, the higher-order, structural relations must be compared on a one-to-one basis between the source and target problems. Analogical encoding supports the induction of problem schemas. In Chapter 12, I describe the reuse of problem analogies from memory by analogy directly with the source problem without attempting to construct a schema.

According to case-based reasoning, problem solving consists of retrieving the nearest case from memory or from an indexed library of annotated problem cases and reusing or adapting it. When a new problem is encountered, most humans attempt to retrieve cases of previously solved problems from memory in order to reuse the old case. If the solution suggested from the previous case does not work, then the old case must be revised (Jonassen & Hernandez-Serrano, 2002). When either solution is confirmed, the learned case is retained for later use. Case-based reasoning is based on a theory of memory in which episodic or experiential memories in the form of scripts (Schank & Abelson, 1977) are encoded in memory and retrieved and reused when needed (Kolodner, 1993; Schank, 1990).

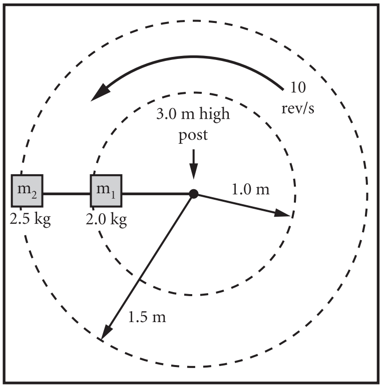
Students' comparisons of source and target analogies should usually be scaffolded with directions or questions. For the analogous problems in Figure 11.1, students were instructed to identify the elements and

Problem A

A puck of mass m = 1.50 kg slides in a circle on a frictionless table while attached to a hanging cylinder of mass M = 2.50 kg by a cord through a hole in the table. The distance from the puck to the hole is 0.02 m and 0.04 m from the hole to the cylinder. What frequency is required to keep the cylinder at rest?



Problem B



Two blocks of masses, m_1=2.0 kg and m_2 = 2.5 kg, are connected to each other and to a central 3 m high post by cords. Blocks 1 and 2 rotate about the post at a frequency 10 rev/s on a frictionless horizontal surface with distances of 1.0 m and 1.5 m from the post, respectively. Assuming the cords are connected to the post and both masses such that they are under tension in directions only parallel to the horizontal surface, what is the tension for each segment of the cord?

Figure 11.1 Problem analogues to be compared and contrasted in order to support problem schema induction.

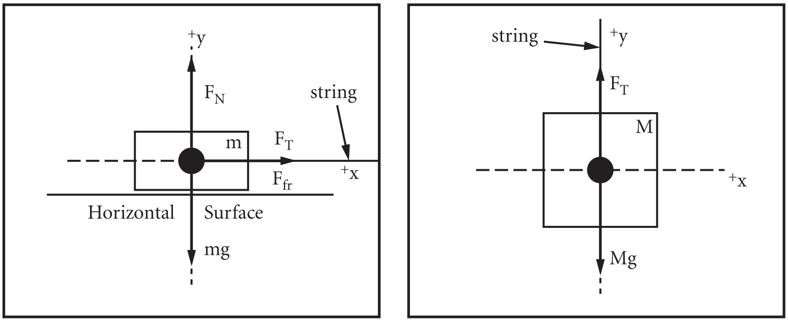


Figure 11.2 Free body diagrams of analogous problems in Figure 11.1. With permission of Fran Mateycik.

their relationships in each problem. In these physics problems, students were directed to construct free body diagrams (Figure 11.2) of each problem to enhance the comparison process. Only then were they instructed to solve the problem using equations.

Presenting problem analogies to students in order to enhance their construction and representation of problem schemas is a potentially powerful instructional strategy. In reality, relatively little research on the use of analogous problems has been conducted (see Chapter 16). Problems as analogies should be compared with problems as prior experiences (Chapter 12).

12

CASES AS PRIOR EXPERIENCES

In Chapters 11 and 16, I describe how problem cases can be used as analogies to help students to learn how to solve problems. In those chapters, structurally similar pairs of problems are presented to students who are supposed to induce more robust problem schemas (see Chapter 15) by comparing and contrasting those problems for similar structural features.

Another way of using cases to support problem solving is by analogy directly with the source problem without attempting to induce a schema. The idea is intuitively known and easily understood. It is called case-based reasoning (Kolodner, 1993; Schank, 1990). The case-based reasoning (CBR) process is described by Aamodt and Plaza (1996) as the CBR cycle (Figure 12.1). Whenever we have a new problem for which a solution is not immediately known, the first thing that we do is to try to remember a similar problem that we have solved in the past. If we have a similar case in memory, we recall the goals, details, and solution and decide whether or not we can reuse that case to help us solve the current problem. The most similar problem usually comes to mind first. If the retrieved problem and current problem match, then we reuse the solution. If the retrieved solution works, then the problem is solved. If it does not work, then we revise the solution and test it. If the revised solution works, then we store that solution along with the particulars of the problem in memory to be retrieved and reused later. With analogical encoding (Chapter 16), case analogies are presented to help learners induce a problem schema. In case-based reasoning, problems remind problem solvers of similar problems they have

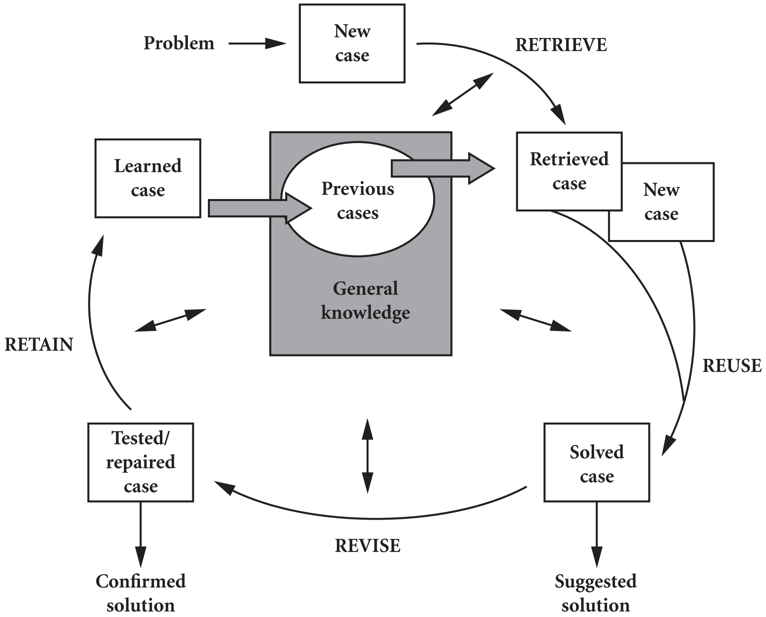


Figure 12.1 CBR cycle (Aamodt & Plaza, 1996).

encountered based on an existing schema. That reminding occurs because the existing problem and the reminded problem are similarly indexed (described later in this chapter).

CBR is based on a theory of memory in which episodic or experiential memories in the form of scripts (Schank, 1999; Schank & Abelson, 1977) are encoded in memory and retrieved and reused when needed (Kolodner, 1993; Schank, 1990). Schank (1990) argues that human intelligence is nothing more than a mental library of indexed stories, despite the absence of any empirical support for that belief. As argued in virtually every chapter in this book, humans represent what they know in multiple ways, including stories. In this chapter, CBR represents useful support in problem-solving learning environments (PSLEs).

WHY DOES CBR WORK?

CBR is based on the assumption that stories are the oldest and most natural form of sense making. Stories are the "means [by] which human beings give meaning to their experience of temporality and personal actions" (Polkinghorne, 1988, p. 11). Cultures have maintained their existence through different types of stories, including myths, fairy tales, and histories. Humans appear to have an innate ability and disposition to organize and represent their experiences in the form of stories. One reason is that stories require less cognitive effort because of the narrative form of framing experience (Bruner, 1990). To be part of a culture, it is necessary to be connected to the stories that abound in that culture (Bruner, 1990). We are surrounded by stories in our everyday and professional lives. Telling stories has many functions:

- a method of negotiating and renegotiating meanings (Bruner, 1990; Lodge, 1990; Witherell, 1995) that allows us to enter into others' realms of meaning through the messages they utter in their stories (Polkinghorne, 1988);
- helps us to learn, to conserve memory, or to alter the past (Bruner, 1990);
- assists us in understanding human action, intentionality and temporality (Bruner, 1990; Huberman, 1995) by facilitating the understanding of the past events of one's life and the planning of future actions (Polkinghorne, 1988);
- aids us in the building of persuasive arguments (Bruner, 1990);
- facilitates the attainment of vicarious experience by helping us to distinguish the positive models to emulate from the negative models to avoid (Polkinghorne, 1988);
- mediates the process of articulating our identity so that we can explain to others who we are with a series of interconnected stories (Polkinghorne, 1988; Schafer, 1981);
- allows us to embark on the authentic exploration of experience from a particular perspective (McEwan & Egan, 1995).

WHAT ROLES DO STORIES PLAY IN PROBLEM SOLVING?

A fundamental assumption of this book is that in our everyday and professional lives we are expected to solve problems. In order to solve problems in those contexts, stories are almost always included in the process. Polkinghorne (1988) found that practitioners primarily prefer to work with narrative knowledge when asked to provide explanations. They seem to be most concerned with people's stories: "they work with case histories and use narrative explanations to understand why the people they work with behave the way they do" (Polkinghorne, 1988, p. x). Schön's (1983) research reveals that the subjects he studied —architects, engineers, and psychotherapists—most often encoded their experiences in narrative form by using case histories and narrative explanations.

This was particularly true of psychotherapists, whose work primarily involves people. These practitioners offered stories to explain and justify their thinking and actions drawing from "a *repertoire* of examples, images, understandings, and actions" (Schön 1983, p. 138; emphasis original). The world of these practitioners revolves around a "virtual world of talk" in which "storytelling represents and substitutes for firsthand experience" (Schön 1983, p. 160). Furthermore, Schön found that intuitive understanding with these practitioners was supported not so much by technical and logical expositions as they were by "their repertoire of familiar examples and themes" (1993, p. 166) as articulated in "stories of past experience which served as exemplars for future action" (1993, p. 242).

In an ethnographic study of problem solving among refrigeration service technicians, Henning (1996) found that stories served as the primary medium for negotiations between technicians, machines, products, and people. Stories afforded technicians a means to form and express their identity as technicians and to assist others in their initiation. By being able to tell stories to their coworkers, technicians were able to form and strengthen the bonds that give cohesiveness to their community of practice. Technicians shared stories about initiation, identity formation, their sense of pride, and in general about the drama of facing unusual and difficult situations. These stories reinforced the technician's identity, which contributed to their further participation in the community they were continuously building.

Orr found that among photocopy technicians "narrative forms a primary element of this practice" (1996, p. 2). He found that diagnosis happens through a narrative process; it formed the basis of the technician's discourse; and it provided "the means for the social distribution of experiential knowledge through community interaction" (Orr, 1996, p. 2). These practitioners employed storytelling for framing and dealing with problems. Narrative was used for:

- explaining catastrophes;
- understanding, explaining and arriving at diagnoses;
- teaching and learning new methods;
- dealing with uncertainty;
- changing perspectives on problems;
- warning about failures;
- providing solutions;
- expanding the problem space;
- finding causes to problems;
- illustrating a point;

- challenging a fellow technician;
- building confidence as problem solvers;
- anticipating future problems.

(Orr, 1996)

For these photocopy technicians, stories are an important source of information that serves as the "community memory of the technicians, in which they preserve and circulate their hard-won knowledge of machine arcane, usually in the form of war stories" (Orr, 1996, p. 117). When called out on a difficult problem, a technician was invariably expected to bring good recollections to bear to the problem situation by producing a good diagnostic story. A good memory of stories of this sort would make a technician "a popular resource" (Orr, 1996, p. 117).

Lave and Wenger (1991) found stories to be also critical for initiating new members into a practice. While studying apprentices in their work setting, they found that "apprenticeship learning is supported by conversations and stories about problematic and especially difficult cases" (Lave & Wenger, 1991, p. 108). In these settings, stories are used as "communal forms of memory and reflection" (Lave & Wenger, 1991, p. 109).

Klein and Calderwood (1988) found that experts (fire commanders, tank commanders, and system designers) relied more heavily on cases based on past experience than on abstract principles when making decisions with a high degree of uncertainty (see Chapter 5). The stories they recalled focused on situational awareness and generating expectancies and options. Ross (1986, 1989b) found that people learning a new skill naturally use what they have learned in a previous problem and apply it to a new problem. Lancaster and Kolodner (1988) found that car mechanics frequently use their experiences and those of others when wrestling with new problems, while Kopeikina, Brandau, and Lemmon (1988) found similar evidence with engineers troubleshooting phone-switching networks. The reuse of cases is essential to learning how to perform complex tasks.

Numerous studies in everyday and professional contexts have shown that narrative is a primary medium for solving problems. The narrative dialogue of reflection and interpretation sustained by these practitioners can be substituted for traditional content knowledge. That is, if stories play such an integral role in everyday problem solving, why should they not play an important role in formal learning settings. In the remainder of the chapter, I describe how stories can be used as cases as prior experiences to support learning how to solve problems.

HOW CAN STORIES (CASES AS PRIOR EXPERIENCES) BE USED TO SUPPORT PROBLEM SOLVING?

In this section, I propose that in order to educate professionals equipped to deal with the complexity of workplace situations (i.e. to solve ill-structured problems) we should expose them to stories generated at the workplace. One way to do this is by exposing them to narratives, stories or cases that have been compiled into a case library (database of stories made available to learners as a form of instructional support). Why should we do this? In business education, Schön recommends conducting a "carefully guided analysis of innumerable stories drawn from real-world business contexts in order to help students develop the generic problem-solving skills essential to effective management" (1983, p. 30). Learners should reflect on the similarities and differences between the problem situation and cases as prior experiences. By being exposed to numerous cases as prior experiences while wrestling with a problem situation, the learner will be expected to reflect in action, while criticizing, restructuring, and testing experienced problems. "Apprenticeship learning is supported by conversations and stories about problematic and especially difficult cases" (Lave and Wenger, 1991, p. 108). Schank (1990, 1999) has consistently argued that relating and listening to stories is the most important element in learning to solve problems.

The use of cases as prior experiences in the form of stories is based on the assumption that stories can function as a substitute for direct experience, which novice problem solvers do not possess. Supporting learning with stories can help students to vicariously gain experience. If you recall the stories that you most like to tell, it is likely that a substantial portion of them were told to you by someone else. They do not represent your direct experience. Some scholars argue that hearing stories is tantamount to experiencing the phenomenon oneself (Ferguson, Bareiss, Birnbaum, & Osgood, 1992). Given the lack of previous experiences by novices, experiences available through stories are expected to augment their repertoire of experiences by connecting with those they have experienced. Their prior experiences serve as a basis for interpreting current and future stories, forewarning us of potential problems, realizing what to avoid, and foreseeing the consequences of our decisions or actions.

WHAT ARE CASE LIBRARIES AND HOW DO WE BUILD THEM?

Case-based reasoning is most often applied to instruction in the form of case libraries of stories that are made available to learners. The stories in the library are indexed in order to make them accessible to learners when they encounter a problem. Those indexes may identify common contextual elements, solutions tried, expectations violated, or lessons learned. Each experience in a case library represents the experiences that others have had while trying to solve problems. What makes case libraries particularly powerful is that they include mistakes as well as successes. Because we learn far more from our errors than we do our successes, being able to access the experiences that resulted in failure by other will help to prevent repeated errors.

The case library may contain the experiential knowledge of potentially hundreds of experienced problem solvers attempting to solve problems that are similar to problem being solved. In addition to providing potential case problems for solving, the case library can also yield an abundance of conceptual and strategic knowledge that may be included in instruction. When eliciting stories, practitioners naturally embellish their stories with contextual information, heuristics, practical wisdom, and personal identities (Jonassen & Henning, 1999; Schön, 1983). In addition to relying only on a conceptual or theoretical description of a system, when a learner is uncertain about what action to take or what hypothesis to make, the learner may access the case library to gain experience vicariously.

How Do We Build Case Libraries?

In order to build case libraries, it is necessary first to elicit and capture relevant stories about previously solved problems from practitioners. These practitioners should not be experts but rather skilled practitioners (journeymen). The goal of capturing stories is to collect a set of stories that are relevant to domain problems and the kinds of information that was relevant to their solution. That is, do the stories in the case library provide lessons to the learner in order to help solve a current problem. In order to collect stories from practitioners, complete the following activities.

1. Identify skilled practitioners in the domain. Skilled practitioners are those who have some years of experience in solving problems similar to the ones that you are analyzing.
2. Show the practitioners the problem(s) for which you are seeking

support, that is, the problem that you want students to learn how to solve. Present one problem at a time. The problem representation should include all of the important components of the problem situation, including contextual information. Alternatively, you can ask practitioners to relate stories of problems that they have encountered on the job and try to match them with problems being taught.

3. Ask the practitioners if they can remember any similar problems that they have solved. If they can (and they usually can), allow them to tell a story about the problem without interruption. Audiotape their recounting of the story. Following their telling of the story, analyze their story with the practitioner. Work with the practitioner to:
   - identify the problem goals and expectations;
   - describe the context in which the problem occurred;
   - describe the solution that was chosen;
   - describe the outcome of the solution. Was it successful? Failure? Why?
   - identify the points that each story makes (i.e., the lessons that it can teach). Prompting practitioners to ensure that all of the necessary information is included is very important.
4. Having collected stories, we must decide what the stories teach us. The final step in the analysis process is to index the stories. Indexing stories is the primary analytic activity in the case-based reasoning process. Schank argued that the "bulk of what passes for intelligence is no more than a massive indexing and retrieval scheme that allows an intelligent entity to determine what information it has in memory that is relevant to the situation at hand, to search for and find that information" (1990, pp. 84–85). We tell stories with some point in mind, so the indexing process tries to elucidate what that point is, given any problem-solving situation. Schank (1990) believes that indexes should include the experience and the themes, goals, plans, results, and lessons from the story. Themes are the subjects that people talk about. Goals motivated the experience. Plans are personal approaches to accomplishing those goals. Results describe the outcome of the experience. The lesson is the moral of the story—the principle that we should take away from the case.

Indexing is the process of assigning labels to cases at the time that they are entered into the case library (Kolodner, 1993). These indexes are used to retrieve stories when needed by comparing new problems to those stored in the case library. Stories can be indexed in two ways. The more common method is through direct input by the human user, who must appropriately index the stories in order to make them accessible in a case library. Stories can also be indexed for case libraries by adapting and reindexing already existing cases to new situations (Kolodner, 1992; Kolodner & Guzdial, 2000). For each case, identify the relevant indexes that would allow cases to be recalled in each situation. Choose from among the following indexes, most of which were suggested by Kolodner (1993). Problem, situation, and topic indexes include:

- What were the goals, subgoals, or intentions to be achieved in solving the problem or explaining the situation?
- What constraints affected those goals?
- Which features of the problem situation were most important and what were the relationship between its parts?
- What plans were developed for accomplishing the goal?

Solution indexes include:
- What solution was used?
- What activities were involved in accomplishing the solution?
- What were the reasoning steps used to derive the solution?
- How did you justify the solution?
- What expectations did you have about results?
- What acceptable, alternative solutions were suggested but not chosen?
- What unacceptable, alternative solutions were not chosen?

Outcomes indexes include:
- Was the outcome fulfilled?
- Were expectations violated?
- Was the solution a success or failure?
- Can you explain why any failures occurred?
- What repair strategies could have been used?
- What could have been done to avoid the problem?

Each story (case) becomes a record in a database. Each case or story is indexed by a case vector that contains a set of attributes (see case-based reasoning architecture in Figure 12.2). Each attribute has a set of members (values) that function as options for case archival and retrieval. The case-retrieval system dynamically creates a query interface for the users by compiling the information stored in the database. It converts the inputs from the users into a query case vector *(Q)* that is then forwarded to the case search engine. The engine retrieves cases using an advanced

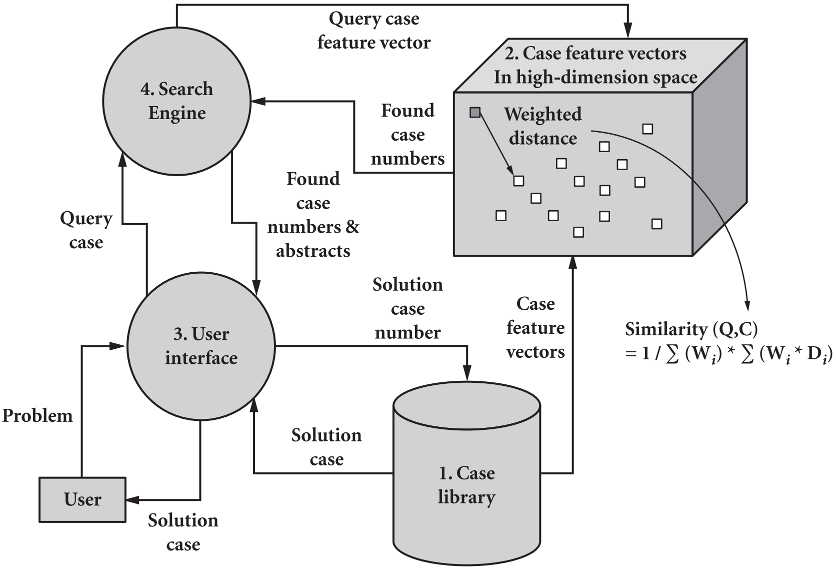


Figure 12.2 Case-based reasoning architecture.

nearest-neighbor algorithm. A meaningful distance measurement is the key to the search engine. When two cases are close to each other, a small distance is expected. Therefore, the search engine first computes the distances between a query case and all database cases. It then ranks the distances to determine the order of retrieved cases so that users are prompted with the best matched case first.

How Do We Use Case Libraries in Problem-Solving Learning Environments?

The process of understanding and solving new problems using case libraries has three parts:

1. recalling old experiences;
2. interpreting the new situation in terms of the old experience based on the lessons that we learned from the previous experience
3. adapting the old solution to meet the needs of the new situation.

(Kolodner, 1992)

Recalling old experiences depends on how well those stories are indexed, that is, how well the characteristics or attributes of the old experience were filed in memory. Better-indexed stories are more accessible and therefore more usable. Interpreting a problem is a process of mapping (comparing and contrasting) the old experience onto the new one, a form of analogical reasoning (see Chapter 11). If the old case offers useful advice or solutions for the new one, then it is used. If not, then the old case is adapted by inserting something new into an old solution deleting something, or making a substitution (Kolodner, 1992). Case libraries may be used as performance support systems when users have their own problems and also as advice in PSLEs.

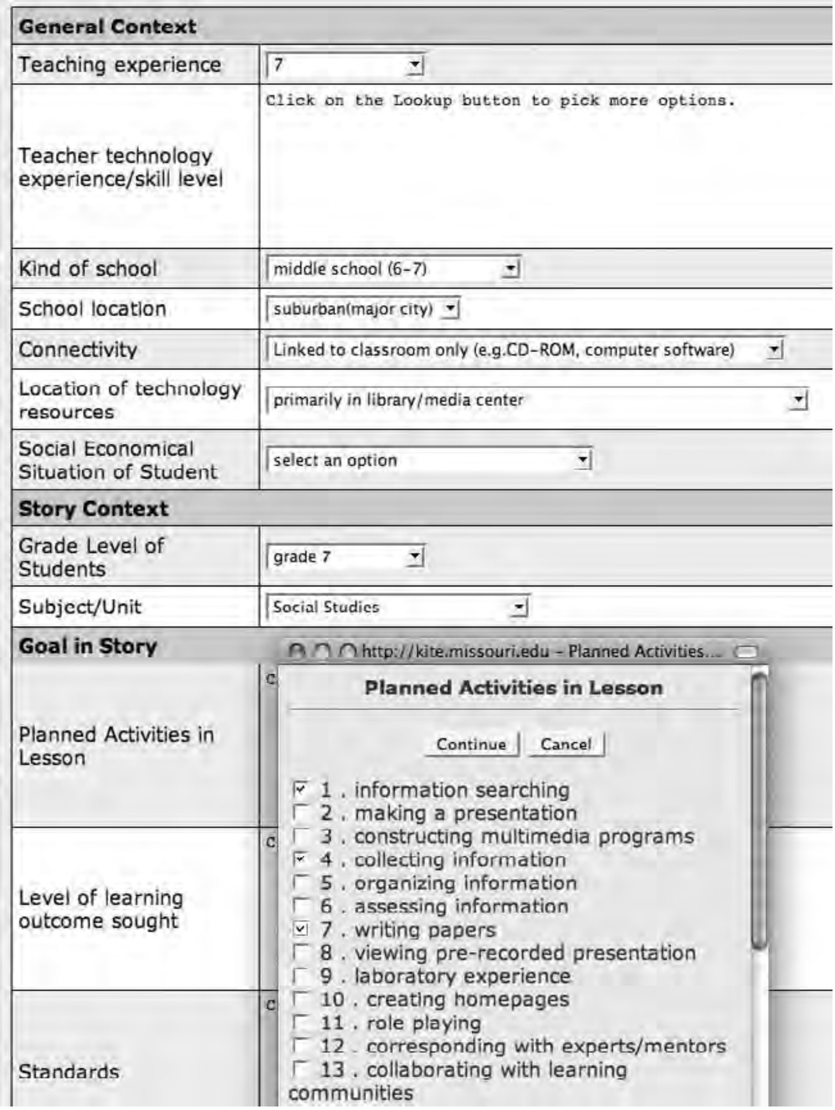
How Can Case Libraries Support Performance?

In the Knowledge Innovation for Technology Integration (KITE) project, a consortium of schools interviewed over 1,000 teachers who told stories of successful and unsuccessful technology integrations (Jonassen, Wang, Strobel, & Cernusca, 2003). Those stories were indexed, and the case library is still available as a just-in-time resource for teachers. When designing lesson planes or trying to figure out how to implement technologies in their classrooms, teachers may access stories in the database by selecting the characteristics of their teaching situation (see Figure 12.3). They are then shown a choice of stories based on the level of the story's match to the characteristics stated by the teacher (see Figure 12.4). Teachers evaluate the applicability of those stories to their own classrooms. That is, the KITE case library supports teacher performance. We have also used it in problem-solving learning environments (PSLEs) to help students to construct meaningful lesson plans (Jonassen & Erdelez, 2005/6).

How Can Case Libraries Support Problem-Solving Learning Environments?

In designing and implementing PSLEs in many contexts, we have developed and integrated case libraries to support problem solving. While designing a learning environment for technology coordinators, our needs assessment showed that the biggest problem that new technology coordinators faced was "how to run a meeting." Additional analysis uncovered consensus building as the real problem. We assigned the learner to work with a committee on different technology issues (see Chapter 8 for a description of the case as problem to solve). There was a coach "standing by" who was accessed via an ask system (see Chapter 18). Based on the questions (see Figure 12.5) the coach would relay stories about how others had handled meeting problems. Students could use or ignore that advice while conducting the meeting.

In another PSLE that we designed for a product-development course in agricultural economics, we developed a case library to provide stories at various decision points. The case in Figure 12.6 is from the "Market Potential" section of the Nestlé case that presents food-product-development problems to college learners. The learning environment



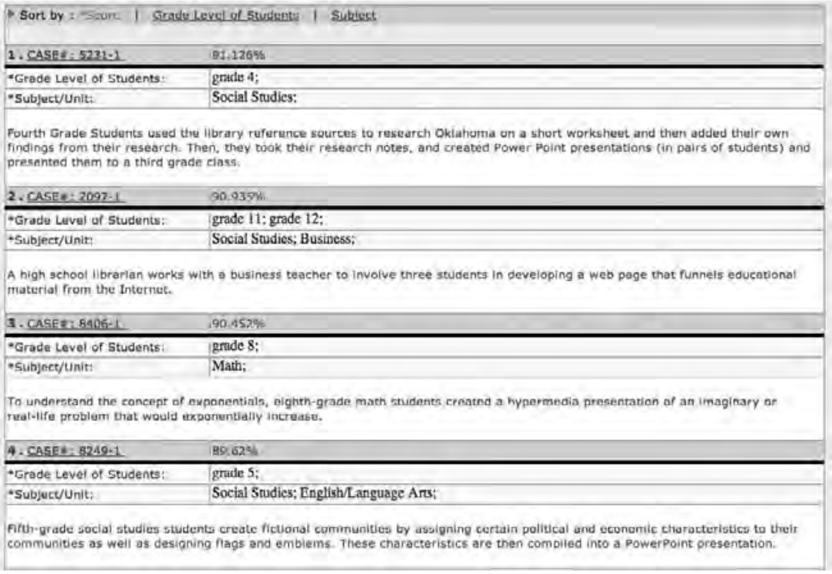
General Context	
Teaching experience	7
Teacher technology experience/skill level	Click on the Lookup button to pick more options.
Kind of school	middle school (6-7)
School location	suburban(major city)
Connectivity	Linked to classroom only (e.g.CD-ROM, computer software)
Location of technology resources	primarily in library/media center
Social Economical Situation of Student	select an option
Story Context	
Grade Level of Students	grade 7
Subject/Unit	Social Studies
Goal in Story	
Planned Activities in Lesson	
Level of learning outcome sought	
Standards	

Planned Activities in Lesson

☑ 1 . information searching
☐ 2 . making a presentation
☐ 3 . constructing multimedia programs
☑ 4 . collecting information
☐ 5 . organizing information
☐ 6 . assessing information
☑ 7 . writing papers
☐ 8 . viewing pre-recorded presentation
☐ 9 . laboratory experience
☐ 10 . creating homepages
☐ 11 . role playing
☐ 12 . corresponding with experts/mentors
☐ 13 . collaborating with learning communities

Figure 12.3 Teacher's selection of characteristics from KITE database.

was set up around eight web pages containing this segment of the case. Specific learning issues are raised on the case at key points in the text, and supportive stories are accessed by learners in order to help them understand these key issues. For example, the first sentence in Figure 12.6 raises the issue of ascertaining potential market size. At the right of this learning issue, the user finds an icon alluding to a story and its



Sort by : *Score | Grade Level of Students | Subject

1 . CASE# : 5231-1	91.126%
*Grade Level of Students:	grade 4;
*Subject/Unit:	Social Studies;

Fourth Grade Students used the library reference sources to research Oklahoma on a short worksheet and then added their own findings from their research. Then, they took their research notes, and created Power Point presentations (in pairs of students) and presented them to a third grade class.

2 . CASE# : 2097-1	90.935%
*Grade Level of Students:	grade 11; grade 12;
*Subject/Unit:	Social Studies; Business;

A high school librarian works with a business teacher to involve three students in developing a web page that funnels educational material from the Internet.

3 . CASE# : 8406-1	90.452%
*Grade Level of Students:	grade 8;
*Subject/Unit:	Math;

To understand the concept of exponentials, eighth-grade math students created a hypermedia presentation of an imaginary or real-life problem that would exponentially increase.

4 . CASE# : 8249-1	89.62%
*Grade Level of Students:	grade 5;
*Subject/Unit:	Social Studies; English/Language Arts;

Fifth-grade social studies students create fictional communities by assigning certain political and economic characteristics to their communities as well as designing flags and emblems. These characteristics are then compiled into a PowerPoint presentation.

Figure 12.4 Selection of stories provided by the KITE database.

What should I do if some individuals don't contribute much?

Technology Coordinator Mary Beth:	Technology Coordinator Tim:
"I've noticed that sometimes people feel intimidated by large groups or are just afraid to speak up if they disagree. If it looks like a particular individual is especially quiet, I try to direct the discussion toward the area related to the topic I know is of particular interest to that person. I also ask people directly to speak up. I might say, "__________, I've noticed you are particularly quiet tonight. Your input is so valuable to the group. Would you share your ideas about ______________ with us. We'd really be interested in what you have to say about this." Once when I tried this, the person I was trying to get to talk ended up talking so much, I had to try to interrupt so we could move on. She just needed a little encouragement to boost her courage."	"At one particular meeting, I was hoping one participant could offer another perspective or solidify a current perspective. I was able to address her directly to elicit a response and discussion. I said, "Monica, what are your thoughts on the current topic?" She felt more comfortable speaking when she didn't have to take the intiative to speak up herself."

Figure 12.5 Stories about running a meeting.

Market Potential

Prior to acquiring Lambert's Pasta & Cheese, Nestlé had ascertained that the potential market size for Pasta and Sauces could be attractive. Now Nestlé retained BASES to conduct a BASES I study, [illegible] assessing the current level of awareness and usage of fresh pasta and fresh pasta sauces, and understanding customer perception of three possible Contadina positioning statements with respect to competitive brands. Additionally NRFC (Nestlé Refrigerated Food Company) wanted to estimate first year trial volume for pasta and sauces,, simulate total Year 1 sales volume, and understand the likely sales effects of alternate positionings.

Figure 12.6 Learning environment for the food product development case library.

main theme. Upon sliding the mouse over it, a popup flashes the story's title that corresponds to an "index" as identified by market-development experts who recounted that story. This index is expected to help make the story memorable and assist in the future story retrieval process. Also, the phrase "Let me tell you a story . . ." appears on the browser's status line at the same time. Students who retrieved those cases as prior experiences while solving food-product-development processes outperformed students who reviewed expository help in lieu of the stories on tests assessing problem-solving skills, such as reminding, identifying, and recognizing the problem, identifying and explaining failure, selecting solutions, adapting solutions, explaining success or alternate strategies, and identifying needed information (Hernandez-Serrano & Jonassen, 2003). These experiential stories helped students to make sense of the ideas they were studying in class by relating them to actual experiences. That is one of the most powerful instructional methods available.

Cases as prior experiences represent an informal approach to learning. Rather than relying on exposition of abstract ideas to convey content, cases as prior experiences enable students to associate ideas with actual experiences. Those cases make the ideas more relevant and meaningful. What more can you ask for?

13

CASES AS ALTERNATIVE PERSPECTIVES

In Chapter 1 and throughout this book, I have distinguished between well-structured problems and ill-structured problems. As described in Chapter 1, well-structured problems are those for which correct answers and solution methods have been identified. For each kind of well-structured problem, there exists a constrained problem schema (see Chapter 15) that describes the kind of problem, the elements comprising the problem, their interrelationships, and solution processes. That is, well-structured problems are interpreted and applied fairly consistently.

Ill-structured problems, on the other hand, may have multiple solutions, solution methods, and solution criteria, so there may be uncertainty about which concepts and methods are necessary to solve the problem. That is, ill-structured problems are interpreted and solved in multiple ways. These problems pervade everyday and professional lives. After completing formal education, most problems with correct answers disappear. In our daily lives, we are constantly faced with problems that have multiple interpretations, perspectives, and solutions. This chapter describes the use of cases as alternative perspectives that may be used to convey those multiple interpretations, perspectives, and solutions. Those multiple interpretations naturally increase the complexity of ill-structured problems. The use of cases as alternative perspectives is based on cognitive flexibility theory (Spiro, Feltovich, Jacobson, & Coulson, 1991; Spiro & Jehng, 1990; Spiro, Vispoel, Schmitz, Samarapungavan, & Boerger, 1987).

WHAT ARE SOURCES OF MISUNDERSTANDING?

Based on extensive research and writing over a number of years, Rand Spiro and his colleagues articulated cognitive-flexibility theory. In that theory, they argue that traditional approaches to instruction have contributed to errors in conceptual understanding, including misunderstanding of important concepts, especially in conceptually complex knowledge domains (Feltovich, Spiro, & Coulson, 1989). This chapter generalizes those beliefs to conceptually complex, ill-structured problems.

Traditional, decontextualized, topic-based forms of instruction attempt to simplify ideas in order to make them more easily transmissible and (hopefully) understandable. Why? The rationale that is most often given for simplifying instruction is that it is impossible to convey appropriate levels of complexity to novices who have inadequate, prior knowledge. Concepts have to be simplified in order to make them understandable—in order to build on the limited, relevant world knowledge that is possessed by novices.

Instruction most often oversimplifies ideas by employing simplified, prototypic examples as single analogies. One of the most powerful yet difficult changes to traditional instruction would be to increase the number of examples provided to communicate ideas. Simple, single examples are easier to conceptualize and implement in most instructions, and complex ideas are easier to study if they are simplified. So, domain content is organized to communicate the reliability and regularity of the content in an attempt to map prestructured content onto the students' knowledge structures. Unfortunately, prestructured content is rigid and therefore not easily adapted to learning contexts outside the immediate instructional context (Spiro et al., 1987). As a result, learners develop a reductive bias in thinking because they are trying to apply overly prescribed knowledge in novel situations that cannot be explained by these simple knowledge structures (Spiro, Coulson, Feltovich, & Anderson, 1988). Simplified content may help students to learn how to solve introductory problems but it impedes the development of knowledge structures necessary to solve more complex and ill-structured problems that pervade our everyday and professional lives.

Traditional content delivery also conveys ideas as context- and content-independent truths, and that knowledge, once acquired, easily transfers to different contexts. On the other hand, contemporary and situated approaches to instruction are primarily concerned with the importance of context in what is learned. I once averred that "context is everything" in learning (Jonassen, 1991a). The underlying assumption of situated theories of learning is that when contextual information is stripped from instruction, the instruction loses its meaning. Instruction should establish and elaborate a context, because information acquired in a real-world context is better retained, the learning that results is more generative, higher order, and more meaningful, and the transfer of that learning is broader and more accurate (Spiro et al., 1987). Contextualization does not mean that it's never appropriate to present abstractions, because learners must abstract ideas in order to transfer them. Nor does this mean that any context is better than no context. Not all contexts are equal. A context works only if it's meaningful to the learner, that is, within their realm of experience or understanding.

Designing instruction to support solving ill-structured problems requires that the ill-structuredness be conveyed, not eliminated. That is, the multiple solutions, solution methods, solution criteria, and theoretical and contextual perspectives that surround ill-structured problems must be communicated. Students must learn to sort through those perspectives to determine the most relevant and important when solving the problems. Spiro and colleagues assume that learners must construct their own interpretation of problems, which requires that they accommodate other perspectives. Problem solving requires the application of knowledge. However, the prepackaged interpretations of reality that students often learn cannot be applied to different problems. The world is not as orderly and predictable as modern theories claim (Taleb, 2007).

Solving ill-structured problems and (to some extent) well-structured problems requires instructional support that can reduce the effects of reductive bias on learning and facilitate advanced knowledge acquisition necessary for solving ill-structured problems. Problem-solving learning environments (PSLEs) that support advanced knowledge acquisition can and should represent the natural complexity that describes most problems.

HOW CAN COGNITIVE FLEXIBILITY THEORY SUPPORT PROBLEM SOLVING?

In order to convey the underlying complexity and ill-structuredness of many problems, cases need to be presented that convey the multiple perspectives that are implicit in ill-structured problems. Cases as alternative perspectives are grounded in cognitive-flexibility theory. When problems to solve are interpreted through different lenses embedded in cases as alternative perspectives, PSLEs can accomplish the following.

How Do We Avoid Oversimplifying Instruction?

Cognitive-flexibility theory stresses the conceptual interrelatedness of ideas and their interconnectedness. PSLEs based upon flexibility theory reflect the complexity that normally faces practitioners, rather than treating practical, professional problems as simple, linear sequences of decisions.

How Do We Provide Multiple Representations of Content?

Most learning theories and nearly all disciplinary instruction are based on the assumption that there is a single, best way to conceive knowledge, that is, there is a single schema or mental model that ought to be assimilated by learners. The role of the teacher or professor is to interpret reality for students and to show them how to think about a subject, rather than forming their own interpretations. This assumption relies on the belief in an objective reality and that there is one true representation of that reality. Over the past two decades, this objectivist assumption has been challenged by more constructivist assumptions that claim that learners individually construct meaning for objects or events based upon the experiences that they relate to them (Jonassen, 1991b). In order to comprehend the complexity of the world, professionals must perceive and reconcile its different interpretations. Transfer of acquired knowledge to novel situations, which is essential in problem solving, requires the understanding of these multiple mental representations that are best achieved through the instructional use of multiple analogies (Gick & Holyoak, 1983). "It is only through the use of multiple schemata, concepts, and thematic perspectives that the multi-faceted nature of the content area can be represented and appreciated" (Jacobson, 1990, p. 21). Cognitive-flexibility theory intentionally represents multiple perspectives or interpretations of contexts in which problems are embedded.

Why Should Instruction Be Based on Multiple Cases?

Rather than basing instruction on a single example or case, it is important that a variety of cases be used to illustrate the content domain. That is the basic assumption of Part II of this book. In PSLEs, that means that students should attempt to solve multiple problems, not just prototypic ones. The more varied these cases-as-problems-to-solve are, the more likely it is that learners will be able to transfer problem-solving skills. Cognitive-flexibility theory stresses case-based instruction. Rather than abstracting ideas and theories from cases (problems), the contextual richness that defines cases needs to be conveyed to learners. So, like most situated conceptions of learning, cognitive-flexibility theory believes that until and unless ideas are conveyed in the context of authentic situations, students will not understand the meanings embedded in the problems and will not be able to sort through the multiple perspectives embedded in each problem.

How Do We Support Complexity?

In order to solve most of life's problems, it is important that learners construct non-compartmentalized, personally relevant knowledge that is not based upon overly prescribed knowledge structures conveyed to the student. Rather than mapping oversimplified models onto the learner, the learner needs to recognize the inconsistencies in that knowledge by applying it in different contexts or relating it to different perspectives while it is being learned. Cognitive-flexibility theory conveys this complexity by presenting multiple representations of the same information and different thematic perspectives on the information. In order to construct useful knowledge structures, learners need to compare and contrast the similarities and differences between cases.

HOW IS COGNITIVE-FLEXIBILITY THEORY IMPLEMENTED?

Cognitive-flexibility theory provides a conceptual model for designing PSLEs to support ill-structured problem solving. The implication of the theory is that for each case as problem to solve, a set of cases as alternative perspectives are provided. Those perspectives provide alternative personal perspectives, thematic perspectives, and disciplinary perspectives that learners must accommodate in order to construct their own interpretation of the problem along with a solution. Because cases as alternative perspectives convey the natural complexity of problems, PSLEs cannot be overly prescriptive in how those cases are presented or sequenced. That is, learners' access to cases as multiple perspectives must be random access and learner controlled.

The most appropriate technological medium for representing cognitive-flexibility theory is hypertext (Spiro & Jehng, 1990). Hypertext is nonlinear or dynamic text that can be randomly accessed. The term "hypertext" was coined by Theodor Nelson (1974) to describe nonsequential writing. In traditional text, the readers or learners are expected to follow the author's organization and sequence of text, which reflects the author's knowledge structure. Hypertext, on the other hand, allows the user immediate access to related text at the moment of need. In hypertext, readers are not necessarily constrained by the author's organization of the text. Because an individual's knowledge structure is unique, the ways that individuals prefer to access, interact with, and interrelate information are also distinct. The ways that learners access and interpret information provided in the hypertext will also depend on the nature of the problem being solved. So, access to and organization of information should be under the control of the learner. In hypertext, users may explore information and even alter it in ways that make the information more comprehensible. The term "hypertext" has been replaced by "hypermedia" (based on multimedia resources available). The most prominent hypermedia knowledge base is the World Wide Web. It is important to note that PSLEs are, by nature, conveyed to learners in hypermedia environments.

WHAT DO PSLEs BASED ON FLEXIBILITY THEORY CONTAIN?

As implied by Part II of this book, PSLEs contain cases. As described in Chapter 8, the focus of any PSLE is the case as problem to solve. Most other kinds of cases embedded in the environment, including the cases as alternative perspectives, function in support of the problem case. Cases as alternative perspectives enable learners to interpret dimensions of the problem in order to generate meaningful solutions.

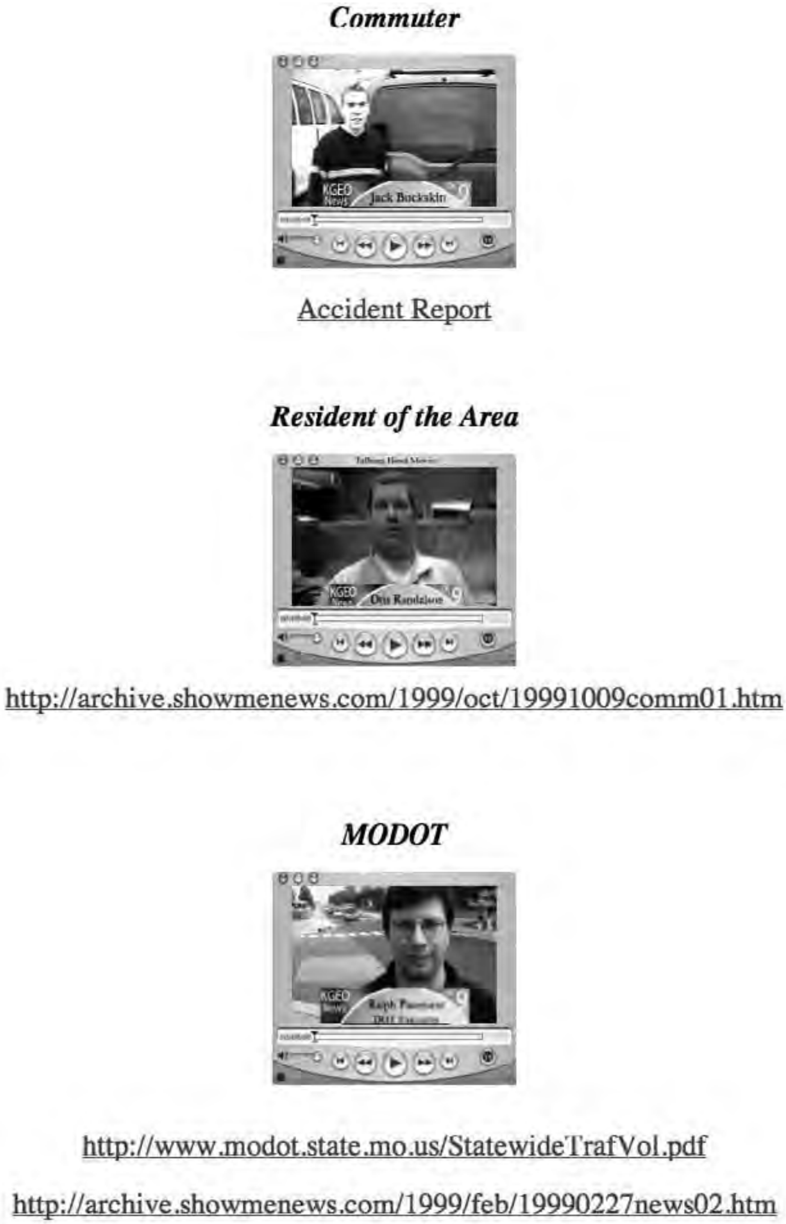
Cases as problems to solve include descriptions of authentic problems. Cognitive-flexibility theory emphasizes case-based instruction. Spiro emphasizes the analysis of mini-cases, cases that have limited conceptual focus. A tendency among subject-matter experts who assume the role of designer is to design gargantuan cases that include a large number of problems and issues. Such cases cannot be analyzed in a reasonable period of time, because even small cases may contain myriad perspectives. In a PSLE that we constructed to support a geography class, we provided a couple of problems that required students to use different maps to design solutions to complex problems. In the first problem, students assumed the role of a member of a consulting firm that had just won a contract to design an alternative route to bypass a poorly designed intersection (see Figure 8.1, p. 165). The second problem involved the choice of where to locate a new landfill for a community. When constructing cases, it is also important to recognize that the complexity, subtlety, and difficulty of the case changes from the beginning to the end of the instructional sequence. Early cases need to be simpler. It is also important to note that cases only work if the learners understand them. Knowledge of the context should be within their realm of experience.

In order to convey the complexity of the road-diversion project described on p. 165, students were presented with multiple perspectives (see Figure 13.1). The cases as alternative perspectives included video interviews with business people, Department of Transportation employees, accident reports, traffic studies, and so on. The alternative perspectives emphasize different issues and often present conflicting interpretations of the problem. Students must work through these problems in order to construct their own interpretation of the problem, which will be required when they file a report containing an argument (see Chapter 20) for their chosen solution. In this environment, similar perspectives were presented for alternative solutions. Perspectives are not always personal. That is, there are many dimensions of perspectives that will play into a problem. In this environment, we provided a series of maps that provided multiple technical perspectives. Maps included a topographic map (Figure 13.2), aerial maps, a real estate (parcel) map, and a soil map (Figure 13.3). The latter is essential. Understanding soil physics is essential for road construction and protecting aquifers when locating a new landfill.

Personal perspectives are relevant to most problems, as just described. However, simply knowing how someone feels about a problem is not sufficient justification for adopting a person's point of view, unless that person happens to be a dictator. Personal perspectives are embedded into PSLEs as cases as alternative perspectives in order to make a point. The points that perspectives make are underlying themes surrounding the issues. In 1997, Mexican gray wolves were reintroduced into the wilderness of Arizona and New Mexico. We developed a cognitive-flexibility hypertext to focus on the problem of public acceptance. We included perspectives from cowboys and ranchers, authors and newspaper writers, and teachers and educators. What did these perspectives mean? We had to interpret the themes that emerged from these perspectives. There were three:

1. consumption vs. conservation
2. confrontation vs. cooperation
3. national vs. local control.

(Rand Spiro prefers that themes be stated in terms of continua.) The ranchers were mostly arguing for local control against government-mandated policies. The environmentalists and the educators were arguing for cooperation rather than confronting the ranchers ("When I think or see a wolf, the quickest thing I want to do is to get my gun and



Commuter

Accident Report

Resident of the Area

http://archive.showmenews.com/1999/oct/19991009comm01.htm

MODOT

http://www.modot.state.mo.us/StatewideTrafVol.pdf

http://archive.showmenews.com/1999/feb/19990227news02.htm

Figure 13.1 Multiple case perspectives on intersection diversion problem.

Figure 13.2 Topographic map of intersection diversion problem.

kill him. He just doesn't belong here"). It is important that students make sense of personal perspectives and weigh their probative value by interpreting their meaning when making decisions. Themes generally emerge from the perspectives that pervade any problem. The front pages of any newspaper are filled with local and national problems for which personal quotes are often elicited. The underlying issues and belief structures that are implied by those perspectives are what students need to learn to synthesize.

Intellectual disciplines are often described by the theories that underlie each discipline. Too often, teachers and professors teach about the theories without relating them to authentic problems or requiring students to actually apply the theories. In a PSLE that supports an introductory sociology course, students are required to solve three problems:

- ☐ Armstrong Lo AM, 5 to 9 % Slopes, Eroded
- ☐ Auvx Asse Silt Lo Am, 0 To 2 % Slopes, Rarely Flooded
- ☐ Bardley-Clinkenbeard Complex, 20 to 45 % Slopes
- ☐ Clinkenbeard-Gasconade-Rock Outcrop Complex 35 to 70 % Slope
- ☐ Freeburg Silt Lo Am, 2 to 5 % Slopes
- ☐ Hatton Silt Lo Am, 2 to 6 Percent Slopes, Eroded
- ☐ Haymond Silt Lo Am, 0 to 3 % Slopes Frequently Flooded
- ☐ Jemerson Silt Lo Am, 0 to 3 % Slopes, Rarely Flooded
- ☐ Keswick Silt Lo Am, 5 to 9 % Slopes Eroded
- ☐ Keswick Silt Lo Am, 9 to 14 % Slopes, Eroded
- ☐ Keswick-Urban Land Complex, 5 to 9 % Slopes
- ☐ Lenzburg Silty Clay Lo Am, 2 to 9 % Slopes
- ☐ Mexico Silt Lo Am, 1 to 3 % Slopes, Eroded
- ☐ Mexico-Urban Land Complex, 1 to 3 % Slopes
- ☐ Perche Lo Am, 0 to 2 % Slopes, Frequently Flooded
- ☐ Rochport-Bonnefemme Complex, 14 to 25 % Slopes
- ☐ Tanglenook Silt Lo Am, 1 to 3 % Sloppes Rarely Flooded
- ☐ Urban Land-Harvestor Complex, 2 to 9 % Slopes

☒ All Soil Types

Figure 13.3 Soil map for intersection diversion problem.

1. decide which person to lease a house to;
2. decide which person to hire as sales director;
3. decide which person to admit to the final freshman slot.

Students research each applicant in terms of a variety of relevant theories. For the job case, students receive an application letter and resumé and then have to investigate each applicant in terms of social-interaction theory, race or ethnicity, gender roles, social-conflict theory, and social class (see Figure 13.4). Rather than defining these theories (which the textbook does a fine job of), each applicant is analyzed in terms of each theory (see Figure 13.5 for an analysis of the case in terms of conflict theory). Students are required to make a decision (see Chapter 3) and then construct an argument to justify their decision in terms of relevant theories and case information (see Chapter 20).

In addition to personal perspectives, thematic perspectives, or disciplinary theoretical perspectives, cases as alternative perspectives may assume different approaches. Rather than teaching students to memorize information about alternative learning theories, educational psychology courses might interpret learning cases in terms of alternative

Dear Hiring Manager,

My name is Otis Watson, you can see my resume as attached. I already have spent my past 18 years in the field of sales and I'm so interested in it.

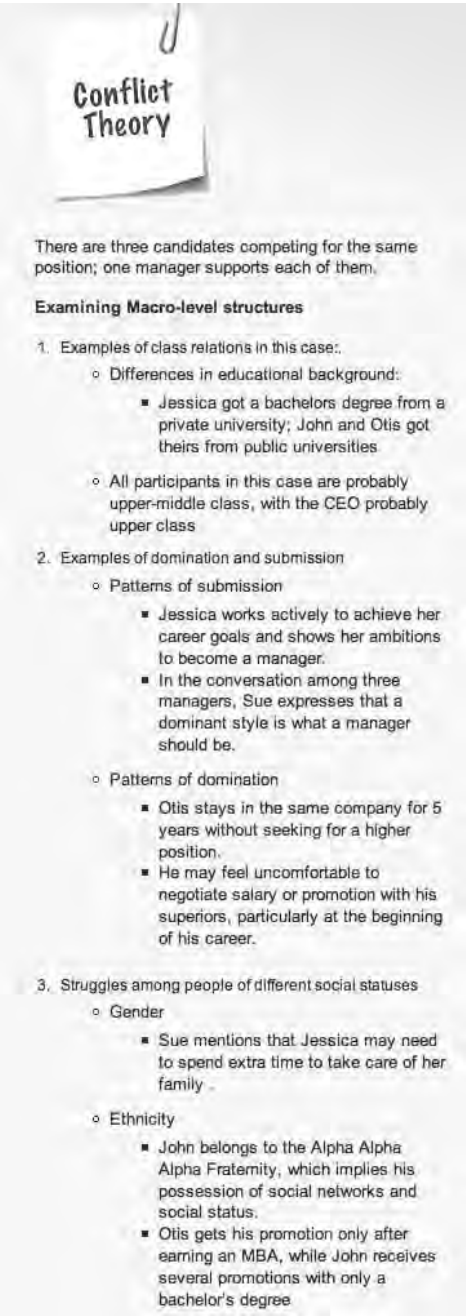
After getting my bachelor degree from SUNY-Stony Brook, I became a Sales and Planning Staff for five years, in my fourth year of working I found out that what I knew was not enough for me to become a good Salesman, then I applied for the Master Program in Columbia University and became a MBA in the next year, at the same time I found a position in Adidas. I worked in Adidas for 7 years, from Sales Associate to Regional Sales Coordinator; Six years ago my boss recommended me a nice position in Ralph Lauren. You can see the details in my resume.

I'm sure I'll be a wonderful Sales Manager if you gave me the opportunity to let me try. Please feel free to contact me.

Thanks a lot!

Sincerely,
Otis Watson

Figure 13.4 Theoretical perspectives on hiring case in sociology course.



Conflict Theory

There are three candidates competing for the same position; one manager supports each of them.

Examining Macro-level structures

1. Examples of class relations in this case:.
    - Differences in educational background:
        - Jessica got a bachelors degree from a private university; John and Otis got theirs from public universities
    - All participants in this case are probably upper-middle class, with the CEO probably upper class
2. Examples of domination and submission
    - Patterns of submission
        - Jessica works actively to achieve her career goals and shows her ambitions to become a manager.
        - In the conversation among three managers, Sue expresses that a dominant style is what a manager should be.
    - Patterns of domination
        - Otis stays in the same company for 5 years without seeking for a higher position.
        - He may feel uncomfortable to negotiate salary or promotion with his superiors, particularly at the beginning of his career.
3. Struggles among people of different social statuses
    - Gender
        - Sue mentions that Jessica may need to spend extra time to take care of her family .
    - Ethnicity
        - John belongs to the Alpha Alpha Alpha Fraternity, which implies his possession of social networks and social status.
        - Otis gets his promotion only after earning an MBA, while John receives several promotions with only a bachelor's degree

Figure 13.5 Conflict theory analysis of job hiring case in sociology course.

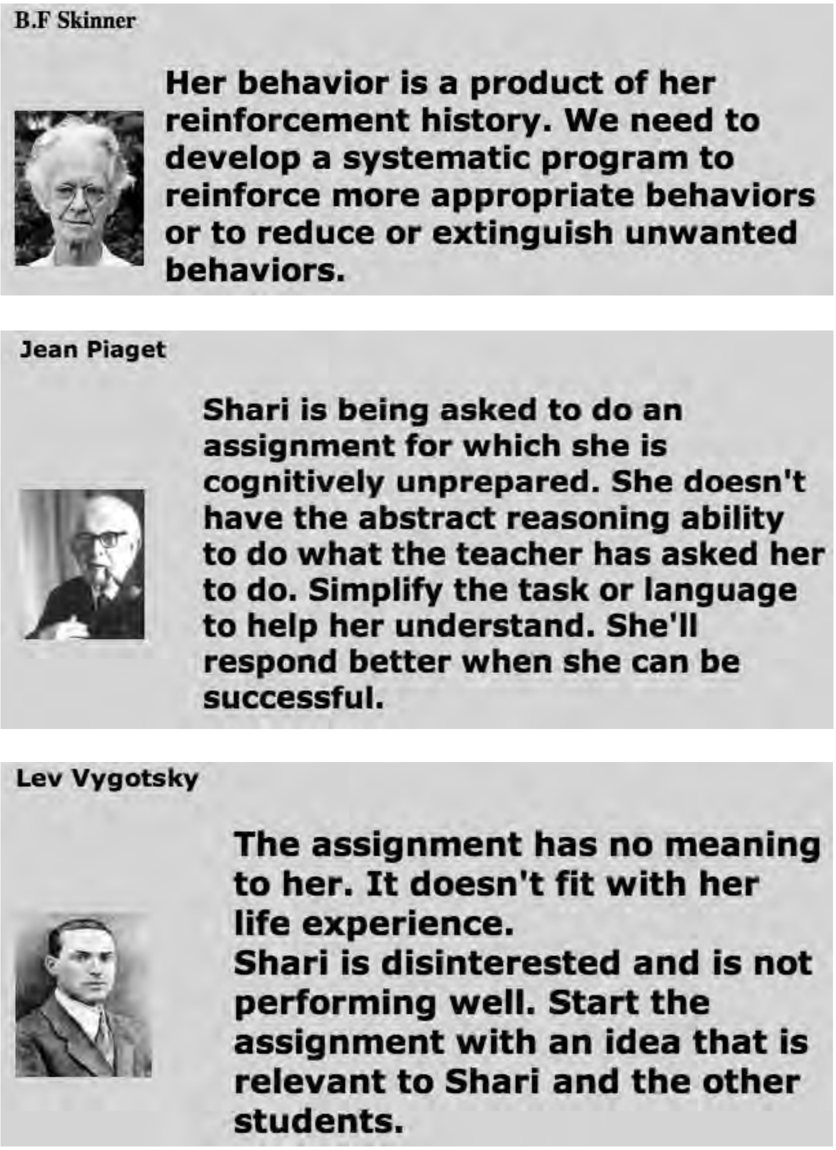
explanatory bases, such as behaviorism, constructivism, situated learning, postmodernism, or structuralism, to name a few. Rather than treating explanatory cases as theories, perspectives might be provided in terms of influential thinkers who represent different perspectives.

For example, in a PSLE on classroom management, one set of perspectives was represented by different theorists in the field (see Figure 13.6). For each classroom-management problem to solve, students would see how Skinner, Piaget, Vygotsky, Bandura, or information-processing theorists would interpret the case. Such a treatment conveys theories as ideas to be applied to interpreting problems, not memorized.

Space limitations preclude providing many more relevant examples of how cognitive-flexibility theory may be applied to PSLEs as cases as alternative perspectives. When designing PSLEs for ill-structured problems, designers must identify the most relevant and powerful perspectives for interpreting various problems to solve. It is not essential that every problem be interpreted using the same perspectives. Different problems necessarily have different perspectives. Cognitive-flexibility theory provides a model of helping learners to address the underlying complexity of problems and provides perspectives that can be used to construct arguments in support of solutions.

HOW SHOULD STUDENTS USE COGNITIVE FLEXIBILITY HYPERTEXTS?

Because cognitive-flexibility theory is normally implemented in random access hypertext that contains multiple cases, perspectives, themes, and/or theories, they are not intended to be studied sequentially. That is, reading a cognitive-flexibility hypertext from front to back would not provide the most benefit. Rather, cognitive-flexibility hypertexts are meant to support analogical comparison of cases, themes, perspectives, and theories (see Chapter 16 for a description of analogical reasoning). In fact, cognitive-flexibility theory grew out of the belief that, although powerful, single analogies are inadequate for deep-level understanding. The solution, of course, is to use multiple analogies in the form of perspectives, themes, theories, etc. So, students should compare and contrast cases in terms of perspectives, themes, or disciplinary perspectives. So a student may analyze a single case in terms of the different perspectives or themes. Or they may compare cases by examining different cases in terms of the same theme. Cognitive-flexibility hypertexts are designed to be accessed nonlinearly in order to support different kinds of problem solving. In order to describe how cognitive-flexibility hypertexts should be used, Spiro borrowed the rich metaphor of



B.F Skinner

Her behavior is a product of her reinforcement history. We need to develop a systematic program to reinforce more appropriate behaviors or to reduce or extinguish unwanted behaviors.

Jean Piaget

Shari is being asked to do an assignment for which she is cognitively unprepared. She doesn't have the abstract reasoning ability to do what the teacher has asked her to do. Simplify the task or language to help her understand. She'll respond better when she can be successful.

Lev Vygotsky

The assignment has no meaning to her. It doesn't fit with her life experience.
Shari is disinterested and is not performing well. Start the assignment with an idea that is relevant to Shari and the other students.

Figure 13.6 Multiple perspectives on classroom management cases.

"criss-crossing the landscape" from Ludwig Wittgenstein for describing that process. Rather than reading from front to back, the learner criss-crosses the intellectual landscape of the content domain by looking at it from multiple perspectives or through themes (illustrated in Figure 13.7). A student may start in a case, examine a perspective, see

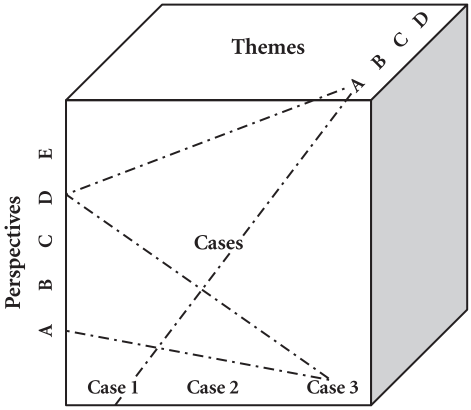


Figure 13.7 Criss-crossing cases, perspectives, and themes.

what theme is inter-related to that perspective, or examine another case in terms of that perspective.

Finally, using cognitive-flexibility hypertexts in a meaningful way relies on a meaningful problem to solve (see Chapter 8), one that requires students to understand it from different perspectives. Decision making and policy problems are perhaps most amenable to cases as alternative perspectives. Those cases should be used in order to help determine the nature of the problem and to examine alternative solutions. Information obtained from the cases, perspectives, themes, and theories should be used to help students to construct arguments (see Chapter 20) in support of their interpretations of or solutions to problems.

14

CASES AS SIMULATIONS

Simulations are important to learning to solve problems. The previous chapters in this section of the book describe the use of cases for helping learners to understand the problem that they are trying to solve and generate meaningful solutions. This chapter describes the use of cases as simulations that will allow learners to practice solving the problem, that is, to try out those solutions. Learning to solve problems requires that learners be able to manipulate the problem elements in some way, that is, to manipulate parameters, make decisions, and affect the environment in some way in order to test the effects of their solutions. Simulation cases provide students the opportunity to interact with a representation of the problem. The form of the simulation will depend on the nature of the activity required to solve the problem. Learners should be directly engaged by the problem that they are exploring so they can experiment with the problem factors and immediately see the results of their experiments. This engagement is best supported by simulations of different kinds.

Simulations are imitations of some phenomenon, state of affairs, or process. Simulations imitate phenomena by allowing learners to manipulate key characteristics or variables within a physical or abstract system. Because of their computational capabilities, computers are usually employed to build simulations of real-life situations. The simulation designer builds a causal model of the phenomena or processes (see Chapter 17) that operationally describes how the system functions. The manipulations that are available are determined that underlying quantitative or qualitative model that runs the simulation, "the main task of the learner being to infer, through experimentation, characteristics of the model underlying the simulation" (de Jong & van Joolingen, 1998, p. 179). When learners interact with the simulation, change values of (input) variables, and observe the results on the values of other (output) variables, they are testing their understanding of the problem. These exploratory environments afford learners the opportunities to test the causal effects of factors (see Chapter 17). Because the learner seldom has access to the underlying model, learners must induce the rule of the model through manipulating the environment.

Simulations are used in a broad range of teaching and training contexts. They vary tremendously in detail and complexity. A search of the Internet will produce hundreds of commercially available educational simulations. For instance, numerous business simulations have been used for decades to training strategic decision making. In the late 1960s, I represented my university in a national business-school competition where we weekly made decisions about twenty-four variables in a complex business simulation. We telexed our decisions to a center that input them into complex simulation software running on a mainframe computer. That was the most engaging activity of my undergraduate career.

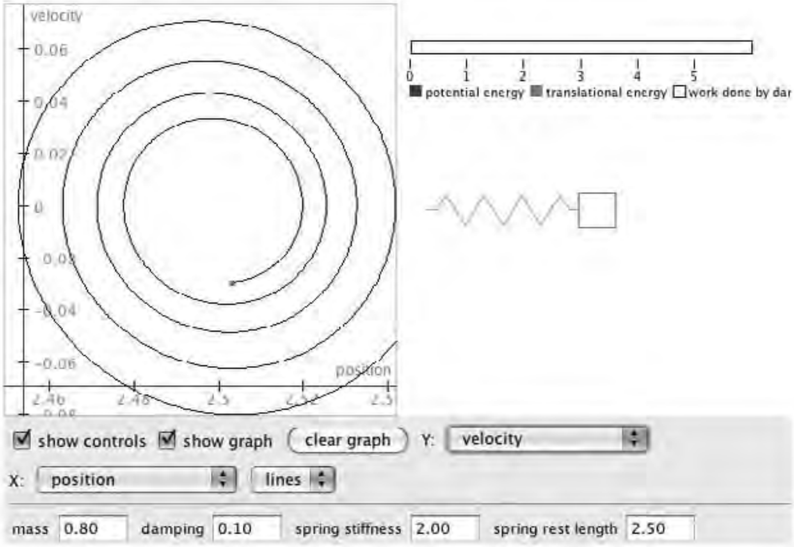
A large number of medical simulations exist to support medical training. These simulations typically present a patient using video and allow the medical trainee to examine the patient, order tests, make diagnoses, and test those diagnoses (inference making) by treating the simulated patient. Those patients may be presented on a computer screen or in the form of a manipulable dummy. Some medical simulations are so complex that they allow medical personnel to conduct simulated surgery. Flight simulators are an important part of pilot training. Pilots can sit in simulated cockpits that even physically move based on flight commands. These simulators can present complex and dramatic situations that the pilots must deal with. A number of planeloads of people have survived airline incidents because pilots had addressed those problems during simulator training. Simulations are used extensively in the trucking industry, and in the military. Among the obvious advantages of simulation use is the ability to learn through mistakes without harming anyone.

Different kinds of simulations exist, including an extensive list of laboratory simulations and urban simulations along with a variety of tools for constructing your own simulations.

WHAT ARE LABORATORY SIMULATIONS?

Among the most commonly available educational simulations are laboratory simulations. Many of these, such as the physics-lab simulation illustrated in Figure 14.1, are available on the Internet (e.g., www.myphysicslab.com). This simulation allows learners to illustrate a single spring experiment in which the learners may set the mass of the block, spring stiffness and damping and graph motion and energy in different forms.

A fascinating biology simulation has been developed by NASA's Classroom of the Future. BioBlast (Figure 14.2; www.cet.edu/products/bioblast/overview.html) is a simulation of a plant-biology laboratory in space where students become scientists trying to feed a space colony while recycling waste products in the process. In Figure 14.2, students set the environmental conditions under which different plants are grown. They have to balance the energy used to grow the plants with the biomass produced. Students receive results on water, oxygen, and energy used and biomass produced, which they must compare with a database of human nutritional needs. Students must abandon preconceptions in order to be able to feed the space colony. It is important in all simulation use that the students suggest and justify their predictions before they test them. The worst thing that you can do is to



☑ show controls ☑ show graph

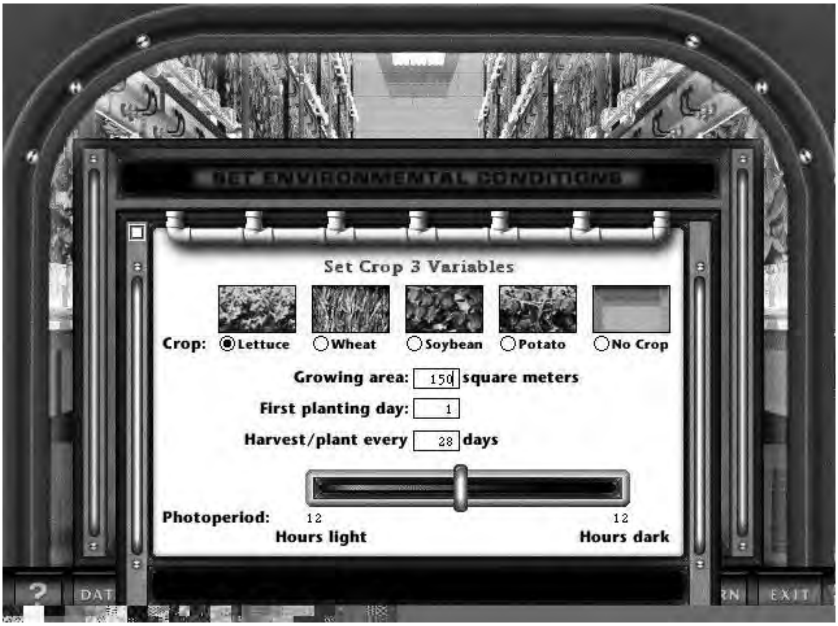
Y: velocity

X: position

lines

mass 0.80 damping 0.10 spring stiffness 2.00 spring rest length 2.50

Figure 14.1 Online physics simulation.



Set Crop 3 Variables

Crop: ● Lettuce ○ Wheat ○ Soybean ○ Potato ○ No Crop

Growing area: 150 square meters

First planting day: 1

Harvest/plant every 28 days

Photoperiod: 12 Hours light 12 Hours dark

Figure 14.2 Setting environmental conditions in BioBlast simulation.

provide a procedural list of actions that students should complete in order to get the right answer. Let them try out several options and fail. When an experiment fails, that is when real meaningful learning begins.

WHAT ARE URBAN SIMULATIONS?

Among the most popular and effective simulations for use in schools (especially social studies) is the urban or city simulator. City simulators were first developed for urban planners to understand how cities are likely to evolve in response to various policy decisions. They often include aspects that we often think of occurring in computerized games (see description of games later in this chapter). SimCity (http://simcity.ea.com) was among the first urban simulations and is now available in several versions. Students make decisions about land use and transportation. While playing SimCity, students can create characters, known as Sims, who will engage other Sims and provide players with feedback on what is going on around the city. Your Sims also experience city life. They get stuck in traffic. Players can also create mountains, valleys, and forests to surround their city as well as causing tornadoes, volcanoes, or meteor showers to challenge the community.

Students can also act as the mayor, who runs the city and connects their city with others in the region that are sharing or competing for resources. The mayor also dispatches emergency vehicles to deal with the natural and unnatural disasters that you create. SimCity also allows group play, computer conferences, and chat lines through the Internet. The complexity of simulations such as SimCity helps students to understand the systemic nature of organizations. Problems in SimCity are political, social, economic, historical, and cultural and cannot be solved using a single perspective. That is the nature of everyday problems that plague real cities throughout the world.

HOW CAN YOU BUILD SIMULATIONS?

When simulations exist that meet your students' learning needs, they should be used judiciously to support meaningful learning. However, it very improbable that you will find a simulation that addresses your specific need, unless you are teaching traditional science courses, for which many laboratory simulations exist. If you are building a problem-solving learning environment for which cases as simulations would prove useful, then you might have to construct your own. Constructing professional games and simulations is far beyond the scope of this book. They require sophisticated models and very complex computer programming to implement. In this book, I briefly describe three approaches to building simulations:

1. constructing learning objects;
2. using systems dynamics tools;
3. employing dedicated simulation builders.

Fortunately, a number of systems have been created to help you to develop simulations.

HOW CAN YOU CREATE LEARNING OBJECTS?

Learning objects can be created using authoring tools such as Authorware, Director, Flash or programming platforms such as Java or JavaScript. These objects may be single use or reusable in different activities. Figure 14.3 illustrates a learning object created by Daniel Churchill (www.learnactivity.com/lo/index.htm) using Authorware and Flash. This object allows learners to test Ohm's Law while trying to solve story problems using Ohm's Law. Students can enter different values for the resistor or the voltage and immediately see the effects. That is, they can visualize the story problems they trying to solve.

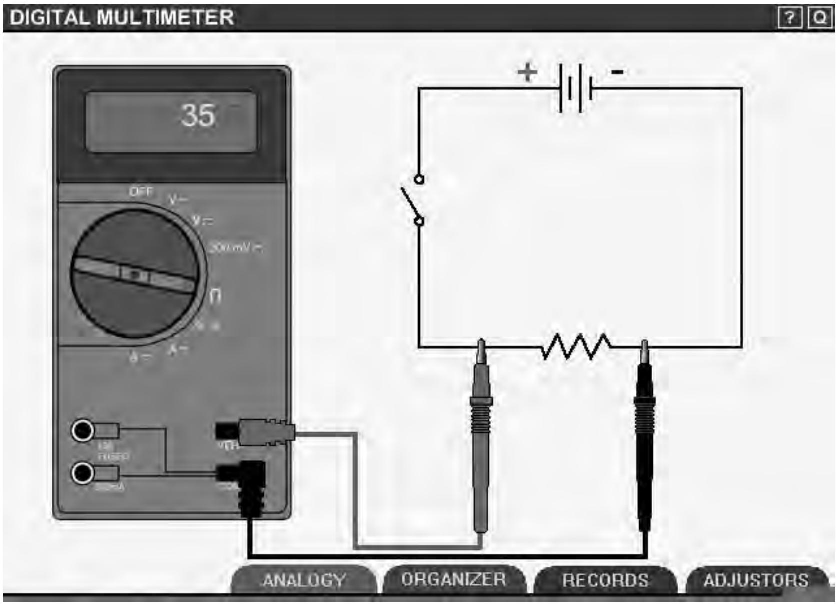


Figure 14.3 Ohm's Law simulation. With permission from Daniel Churchill, Learnativity.

Figure 14.3 illustrates a learning object that provides students with a voltmeter to use when troubleshooting electronic circuits. In principle, learning objects can be complex. In practice, however, because they are designed to be reusable, the scope of most learning objects is limited.

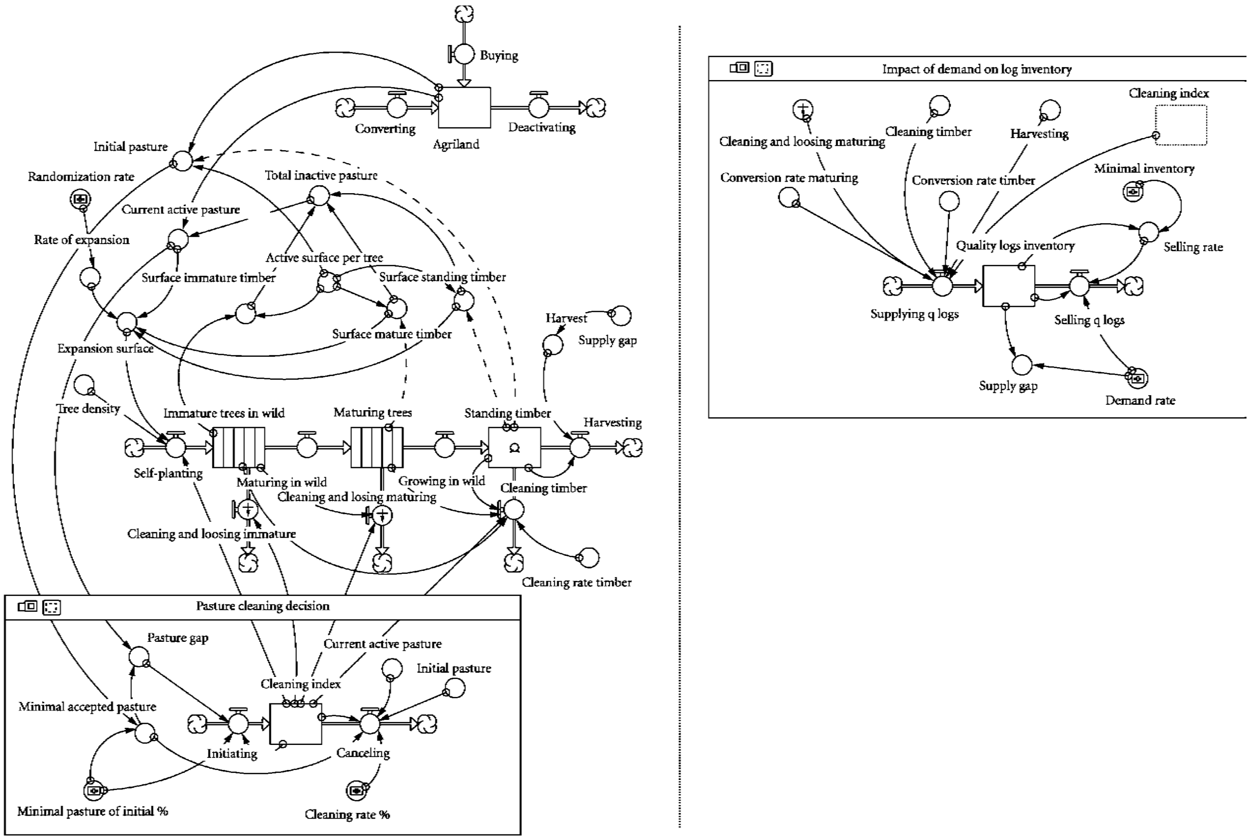
HOW CAN YOU USE SYSTEMS DYNAMICS TOOLS?

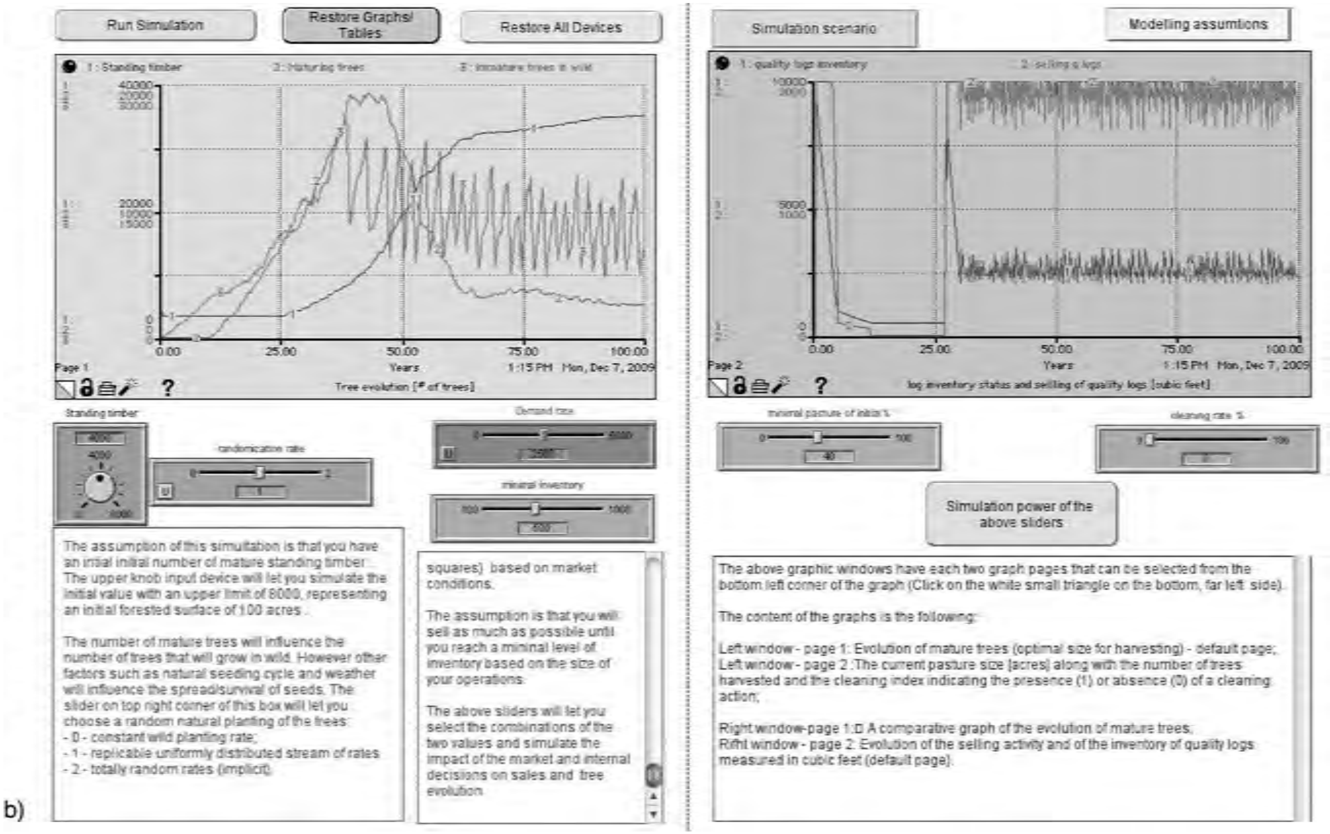
There exists a class of systems dynamic tools, including Stella, VenSim, and PowerSim, with which you can to build these dynamic simulations. These tools use accumulations and flows as the primary modeling tools. For example, the systems model in Figure 14.4a was built using Stella and represents a forestry problem. Stella uses a simple set of building-block icons to construct a map of a process: stocks, flows, converters, and connectors (see Figure 14.4a). Stocks illustrate the level of some thing in the simulation. In Figure 14.4a, AgriLand, *immature trees in wild, maturing trees*, and *standing timber* are stocks. Flows control the inflow or outflow of material to stocks. *Self-planting, growing in wild,* and *maturing in wild* are flows. Flows often counterbalance each other, like positive and negative influences in causal loops. For example, *growing in wild* has a positive influence on *standing timber*, which is reduced by *harvesting*. Converters convert inputs into outputs. They are factors or ratios that influence flows. *Rate of expansion* is a converter that controls both *expansion surface* and the flow *self-planting*. Converters are used to add complexity to the models to better represent the complexity in the real world. Finally, connectors are the lines that show the directional effect of factors on each other by the use of arrows. Students generate equations in the stocks and flows for numerically representing relationships between the variables identified on the map using any kind of mathematical formalism from simple arithmetic to differential equations. Once a model has been built, Stella enables learners to manipulate variables and run the model that they have created and to observe the output in graphs, tables, or animations (as shown in Figure 14.4b). Being able to test the effects of changes in the variables is the true power of simulations. It requires students to understand causal relationships and make and confirm hypotheses (discussed later).

HOW DO YOU USE SIMULATION BUILDERS?

A few simulation-building tools exist. Using these tools, authors can describe the underlying model and build an interactive interface. Perhaps the best of these tools is SimQuest (www.simquest.to.utwente.nl). Using SimQuest, authors have built a simulation of a sewage plant (Figure 14.5). The application is part of a series of courses about wastewater technology and can be used as starting and end point of such a course. The students in this simulation get to operate a working sewage plant. This simulation may be useful in learning how to troubleshoot problems in such a plant.

Simulations can also be programmed into interactive websites. We have constructed a number of case-analysis environments. Case-analysis problems are more difficult to simulate, because they are usually complex and many of the factors cannot be quantified so they cannot be simulated in a quantitatively modeled simulation. Simulating case-analysis problems relies on complex causal reasoning; however, the kind of causal reasoning in case-analysis problems is usually modeled using qualitative representations (see Chapter 19) rather than the quantitative models that underlie story problems and troubleshooting problems. Therefore, these kinds of simulations must be constructed using a qualitative (If-THEN) model of the factors and interactions that are specific to the problem being solved. In a problem-solving learning environment on consensus building that we built (which a needs assessment showed to be the most important skill for technology coordinators), the student attends a short meeting in the a)


Buying
Converting
Agriland
Deactivating
Initial pasture
Randomization rate
Total inactive pasture
Current active pasture
Rate of expansion
Active surface per tree
Surface immature timber
Surface standing timber
Surface mature timber
Expansion surface
Harvest
Supply gap
Tree density
Immature trees in wild
Maturing trees
Standing timber
Harvesting
Self-planting
Maturing in wild
Growing in wild
Cleaning and losing maturing
Cleaning timber
Cleaning and loosing immature
Cleaning rate timber
Pasture cleaning decision
Pasture gap
Current active pasture
Initial pasture
Cleaning index
Minimal accepted pasture
Initiating
Canceling
Minimal pasture of initial %
Cleaning rate %
Impact of demand on log inventory
Cleaning index
Cleaning and loosing maturing
Cleaning timber
Harvesting
Minimal inventory
Conversion rate maturing
Conversion rate timber
Quality logs inventory
Selling rate
Supplying q logs
Selling q logs
Supply gap
Demand rate



The assumption of this simulation is that you have an initial initial number of mature standing timber. The upper knob input device will let you simulate the initial value with an upper limit of 8000, representing an initial forested surface of 100 acres .

The number of mature trees will influence the number of trees that will grow in wild. However other factors such as natural seeding cycle and weather will influence the spread/survival of seeds. The slider on top right corner of this box will let you choose a random natural planting of the trees:
- 0 - constant wild planting rate;
- 1 - replicable uniformly distributed stream of rates
- 2 - totally random rates (implicit).

squares) based on market conditions.

The assumption is that you will sell as much as possible until you reach a mininal level of inventory based on the size of your operations.

The above sliders will let you select the combinations of the two values and simulate the impact of the market and internal decisions on sales and tree evolution.

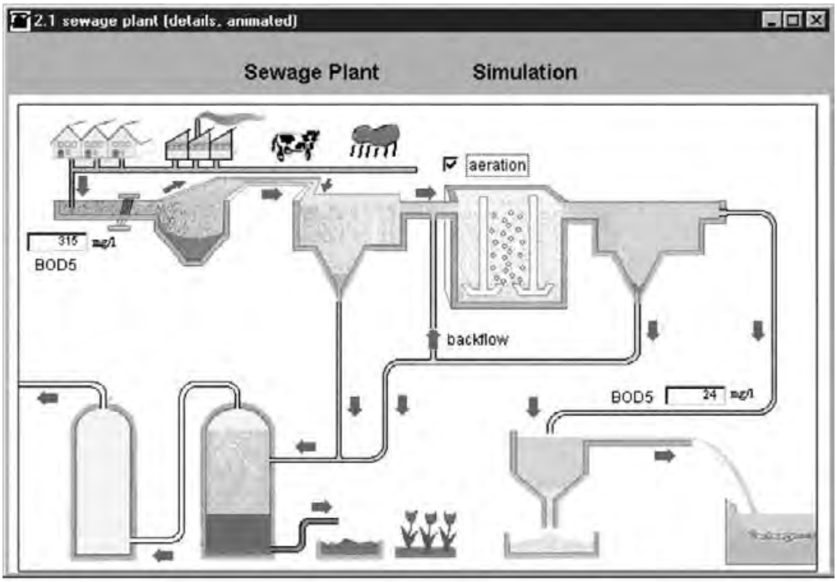
The above graphic windows have each two graph pages that can be selected from the bottom left corner of the graph (Click on the white small triangle on the bottom, far left side).

The content of the graphs is the following:

Left window - page 1: Evolution of mature trees (optimal size for harvesting) - default page;
Left window - page 2 :The current pasture size [acres] along with the number of trees harvested and the cleaning index indicating the presence (1) or absence (0) of a cleaning action;

Right window-page 1:□ A comparative graph of the evolution of mature trees;
Rifht window - page 2: Evolution of the selling activity and of the inventory of quality logs measured in cubic feet (default page).

Figure 14.4 (a) Systems model of forestry project; (b) simulation controls and graphic output of model in (a).



☑ aeration

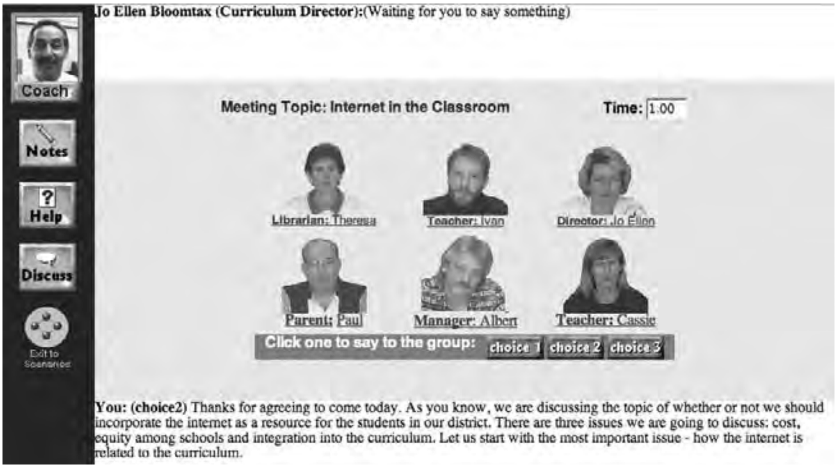
Figure 14.5 Simulation of sewage plant.

superintendent's office, where the superintendent charges the learner with the following task:

> Hello there! I'm Judith Johnson, the Superintendent of the school district. Thanks for coming! We are having some serious disagreements in our Technology Committee meeting today about whether or not our school should provide the Internet as a resource to the students during class this year. I sure hope you can help the meeting members reach some common ground.
>
> I have another meeting, so I need to run. When you think you've helped the group reach agreement on this issue, please send me your notes on the strategies you used. Good luck!

The student in this environment enters the simulated meeting room (Figure 14.6) where he or she gets to meet and interact with the committee. In the meeting room, the student can get background information on each of the committee members and advice from the coach before selecting what to say to the committee. The interaction in this simulated environment is between the student and the virtual committee.

Simulations work because they provide direct performance feedback. At each time frame in the simulation, the student has a choice of things



Jo Ellen Bloomtax (Curriculum Director):(Waiting for you to say something)

You: (choice2) Thanks for agreeing to come today. As you know, we are discussing the topic of whether or not we should incorporate the internet as a resource for the students in our district. There are three issues we are going to discuss: cost, equity among schools and integration into the curriculum. Let us start with the most important issue - how the internet is related to the curriculum.

Figure 14.6 Meeting room in consensus-building simulation.

that he or she can say to the committee. Each choice usually pleases some of the members (they smile) and displeases others (they frown). We could have added meters to each of the committee members, such as attention, anxiety, or satisfaction meters, to indicate their state of mind at any point in the negotiations. While this scenario is merely a simulation of a meeting, the learners become engaged, and, as I have pointed out repeatedly, without engagement, there is no meaningful learning. The feedback provided by the simulation enables students to confirm or modify their models of the system. Those models include all of the causal relationships that are represented by the variables in the simulation.

HOW EFFECTIVE ARE SIMULATIONS?

Much of the early research on the effectiveness of simulations showed no benefit. The lack of effectiveness is attributable to many factors, including lack of conceptual understanding of the relationships among the variables in the simulation. Playing with a simulation does not necessarily lead to deep engagement with the simulation. That requires understanding of the causal relationships among the variables. That understanding relies on making informed predictions prior to running the simulation and reflection on the results of the simulation with possible adjustment of the predictions.

An extensive review of early research on simulations by de Jong and van Joolingen (1998) summarized the problems in using simulations that lead to their lack of effectiveness. Those problems include poor hypothesis generation, ineffective design of experiments using the simulation, and inaccurate interpretation of the data resulting from the simulation. All of these are related to poor problem schemas or deficient metal models of the variables included in the simulation. Additionally, they found that students were not effective in regulating their discovery learning behavior (see Chapter 21 on metacognition). Learning through running simulations requires very mindful, self-regulated learning. In the next section, I briefly describe scaffolds for enhancing simulation use.

HOW DO WE SCAFFOLD STUDENT LEARNING WHEN USING SIMULATIONS?

Having articulated the problems that learners experience while learning through simulations, de Jong and van Joolingen (1998) recommend a variety of instructional supports. First, they recommend direct access to domain knowledge. For me, that means access to conceptual models of the problem being solved, preferably in the form of influence diagrams that convey the functional (causal) relationships among the elements in the problem (see Chapter 17). In Chapter 4, I described multi-layered maps that describe the system being troubleshot, including topographic, functional, and strategic layers. Domain knowledge needs to be available, but it needs to be available in a readily usable form.

De Jong and van Joolingen (1998) also recommend support for making predictions and generating hypotheses. Those supports include hypothesis menus (Shute & Glaser, 1990) and hypothesis scratchpad (van Joolingen & de Jong, 1991). I imagine a hypothesis-construction tool with side-by-side menus for connecting causes with effects and predicting the size and direction of effect. Another useful model for supporting hypothesis generation is the PARI (precursor, action, result, interpretation) model (Hall, Gott, & Pokorny, 1995) where learners select an action to be taken, a hypothesis that warrants that action, the results of that action, and finally an interpretation of the results.

Two types of scaffolds appear obvious for use with simulations: question prompts and modeling. Question prompts can be used to focus student attention on the causal relationships that define the underlying simulation model. We have used such questions to enable students to identify the problem elements needed to generate hypotheses (see Figure 14.7). Question prompts are used extensively by researchers to support self-regulation of their learning processes (see Chapter 21).

The **speed** of the projectile when it strikes the ground below would increase (with respect to situation in the original problem) if (select all that apply)

a. Mass of the projectile increases (alone)
b. The firing angle increases (alone)
c. Initial height of the projectile (height of the cliff) increases (alone)
d. Initial speed the projectile increases (alone)

Figure 14.7 Questions that support hypothesis generation.

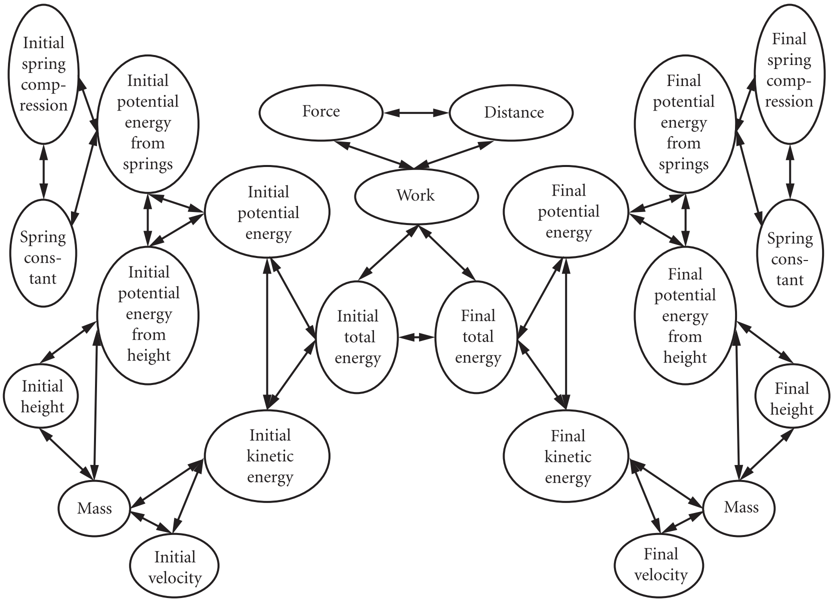


Figure 14.8 Structure maps of work–energy problems.

Hypothesis-generation questions may also be enhanced through the use of structure maps (Figure 14.8). The structure map in Figure 14.8 illustrates all of the possible components of any work–energy problem in introductory physics. Using the map, students identify the:

- physical quantities that are given in the problem;
- physical quantities that are asked for in the problem;
- path that allows them to start with the given quantities and takes them to the quantities that are asked for in the problem.

This kind of analysis helps learners to identify causal relationships and to convert them into hypotheses as well as equations.

Another powerful scaffold for helping students to learning through simulations is the construction of qualitative models of the problem being simulated (see Chapter 19). Simulations are built on quantitative (covariational) descriptions of causal relationships (see Chapter 17). Students need to integrate qualitative representations with those quantitative. Constructing models of problems using expert system editors (see Chapter 19) will force students into articulating relationships among problem variables.

Expert systems are simulations of intelligent decision making (see Chapter 19). They provide qualitative representations of various actions. The small expert in Figure 14.9 reflects on the decisions required while running a simulation of a trickling water-filter system. Reflecting on the thought processes involved in running a simulation induces the model underlying the simulation. Expert systems provide a powerful form of reflection.

Systems dynamics tools were described earlier as means for constructing simulations for student use. They may also be used by students to construct their own models and simulations of problems. For example, the model in Figure 14.10 describes carbon-dioxide exchanges in a plant-producing biomass. This is a more complex problem that relies on a more complex model. I have argued for years (Jonassen,

```
Context 'Changing the recirculation flowrate of a trickling filter
system'
1D1: Decrease flow
1D2: 1Increase flow
1D3: 1Maintain flow
Q1: What is the efficiency of removal of organic waste?
     Why '1Trickling filter system has to achieve certain removal
     efficiency. In this case 85%.
A1: <85%
A2: 1>85%
Q2: What is the hydraulic load?
     Why 'Hydraulic loading can help determine if flooding in the filter
     will occur.  Assume design factor for hydraulic loading to be 10
     m/d.,'
A1: 1<10 m/d
A2: 10m/d
A3: 1>10 m/d
Q3: How much is the organic loading?
     Why '1Organic loading determines the concentration of organic waste
     to be treated.
A1: 1Low
A2: 1Medium
A3: High
Rule 1: IF (q1a1 and q2a1 and q3a1) or (q1a1 and q2a1 and q3a2) or (q1a1
        and q2a1 and q3a3) THEN D2
Rule 2: IF (q1a2 and q2a2 and q3a1) or (q1a2 and q2a2 and q3a2) or (q1a2
        and q2a2 and q3a3) THEN D3
Rule 3: IF (q1a2 and q2a1 and q3a3) or (q1a2 and q2a1 and q3a2) or (q1a2
        and q2a1 and q3a1) THEN D11111
Rule 4: 1IF (q1a1 and q2a2 and q3a3) or (q1a1 and q2a2 and q3a2) or
         (q1a1 and q2a2 and q3a1) THEN D3
Rule 5: 1IF (q1a2 and q2a3 and q3a3) or (q1a2 and q2a3 and q3a2) or
         (q1a2 and q2a3 and q3a1) THEN D3
Rule 6: 1IF (q1a1 and q2a3 and q3a3) or (q1a1 and q2a3 and q3a2) or
         (q1a1 and q2a3 and q3a1) THEN D3
```

Figure 14.9 Expert system reflection of filter system.

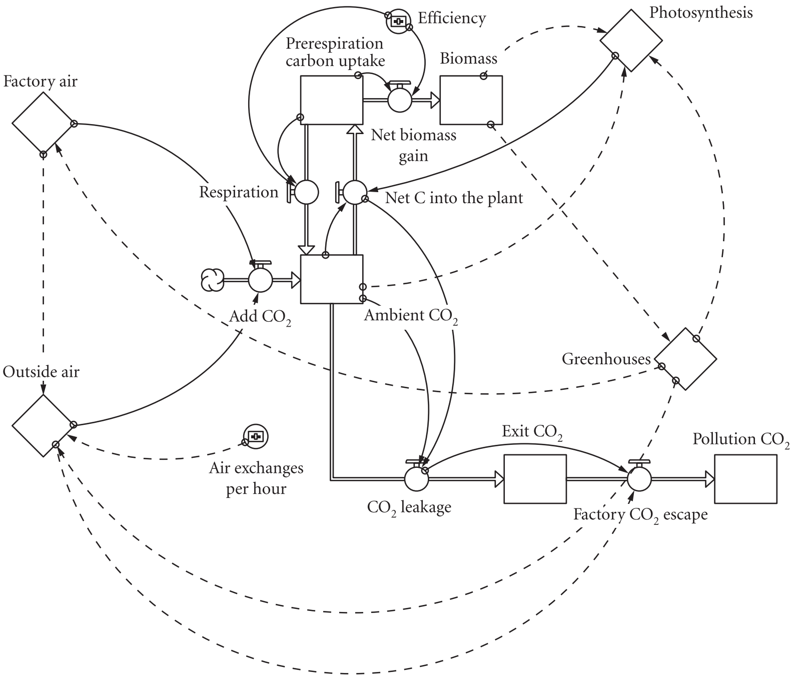


Figure 14.10 Systems dynamics model of biomass production.

2000a) that students learn more from constructing models than they do from interacting with models that others have constructed.

Using simulations without reflecting on the results of learner manipulations will not likely improve learning or performance. Students must integrate results of their manipulations with their schemas (Chapter 15) for the problems being simulated. Meaningful learning through simulations requires students to reflect on and explain the results in light of their expectations. This is known as reflection-on-action (Schön, 1983).

PART III

COGNITIVE SKILLS IN PROBLEM SOLVING

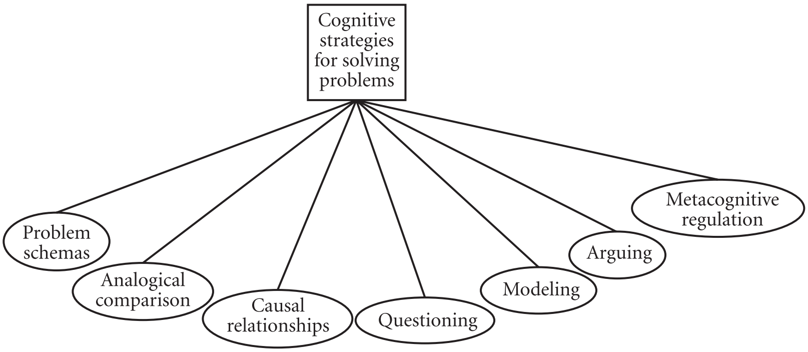


Figure III.1

As indicated at the beginning of the book, different kinds of problems require different cognitive skills to solve. In Part III of this book, I describe how those cognitive skills are supported in problem-solving learning environments (PSLEs). Each chapter in Part III describes different cognitive skills that are operationalized as cognitive strategies in each of the chapters.

Chapter 15	Defining the Problem: Problem Schemas
Chapter 16	Analogically Comparing Problems
Chapter 17	Understanding Causal Relationships in Problems
Chapter 18	Question Strategies for Supporting Problem Solving
Chapter 19	Modeling Problems
Chapter 20	Arguing to Learn to Solve Problems
Chapter 21	Metacognitive Regulation of Problem Solving

As indicated in the chapters in Part I, the specific cognitive skills that are engaged by problems depend on the kind of the problem being solved.

15

DEFINING THE PROBLEM

Problem Schemas

The goals of learning to solve problems include not only finding an acceptable solution to any problem but also being able to recognize similar problems at a later date in order to reduce the amount of mental effort required to solve a transfer problem at that time. That is, an important goal for students is to learn what kind of problem they are solving. In order to do that, they must construct a problem schema for each kind of problem being solved. Note that constructing problem schemas is difficult, but it is much easier for well-structured problems, for which there are known problem types. For ill-structured problems, it may not be possible to identify specific problem schemas; however, as Chapter 12 describes, people are reminded of problems when required to solve new ones. What enables them to remember previous problems is the problem schema that they constructed based on their experience.

A problem schema is a concept that we form for a particular kind of problem. As described in Chapter 9, concepts (schemas) are the bases of human understanding and reasoning. Concepts represent interpretations of things in the world that humans construct. Concept categorization is the most pervasive cognitive process in everyday life (Rehder, 2003) as we access terms to describe what we are thinking or interpret what others say to us. Constructing concepts of problems is an important learning outcome.

WHAT ARE PROBLEM SCHEMAS?

Rumelhart and Ortony (1977) introduced the concept of schema as a form of knowledge structure used to identify the type of problem being solved. Problem schemas include semantic information and situational information about the problem associated with the procedures for solving that type of problem. Greeno and his colleagues first articulated the nature of problem schemas by describing elementary mathematics problems (see Chapter 2 for more detail on problem schemas). They believed that understanding quantitative relationships in problems requires more than the equations that express them and that conceptual understanding of the problem structure is essential (Riley, Greeno, & Heller, 1983). They argued that problem types vary by semantic structure (e.g., combinations vs. comparisons of values in arithmetic) and by the location of the unknown quantity in the formula. The simplest classes of story problems in elementary mathematics include combine, change, and compare problems. Within each class of problem, the unknown may be the result, the amount of change, or the starting quantity stated in the problem. So, understanding a problem includes two processes: representing patterns of information in the meanings of terms in the text and constructing a conceptual model that represents the situation in the text. For example:

> Tom has three apples. Mary gave Tom three more apples. How many apples does Tom have in the end?

This is an example of a combine problem with the unknown in the result.

A compare problem with the unknown as the amount of change would look like this:

> Tom has four apples. Mary has some apples. Altogether, they have nine apples. How many apples does Mary have?

Representing the patterns of information in different problem schemas relies on the semantic associations between each of the problem elements. The more important associations depict structural relationships between the problem elements. For example, the conceptual model for the second *combine* problem (above) is illustrated in Figure 15.1. That model identifies the sets that comprise the problem. In combine-story problems, each set is similar. The only difference between sets in Figure 15.1 is Mary's set, where the quantity is unknown. *Change* problems and *compare* problems can be depicted by similar conceptual models. The major difference in those models are the links

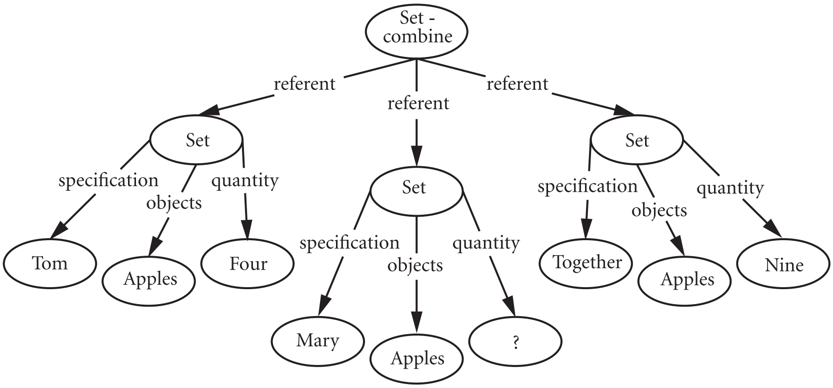


Figure 15.1 Semantic network of combine problem schema.

between the entities. Rather than combine links, they include change or comparison links.

What Structural Properties Are Important in Problem Schemas? Constructing robust problem schemas is important to learning to solve problems in any domain. Most of the research on problem-schema development is been conducted with physics problems. In Chapter 2, I showed how students who excel on quantitative exam problems fail to develop robust problem schemas. When students memorize equations and mimic problem-solving procedures they fail to understand the concepts behind the equations. If students are unable to identify the relevant sets in the problem presentation and assign them to some kind of conceptual model based on domain principles, it is unlikely that they understand the point of the problem and even less likely that they can transfer any solution processes to new, structurally similar problems. In addition to understanding the domain propositions underlying the problem, solving story problems also requires construction of generic propositions, such as quantity (number, some, how many), possession (have, give), compare (more than, less than), and time (past, beginning, then). Problem solvers construct their understanding of a problem by arranging the structural and generic propositions of the text into a coherent conceptual model. In algebra problems, for instance, there are three general kinds of generic propositions that describe sets and relations between sets (Hall, Kibler, Wenger, & Truax, 1989).

1. The **assignment proposition** assigns a single numerical value to some variable (e.g., cost of candy = $1.70; time to fill one pipe is 6 hours; total amount invested = $4,000).

2. The **relation proposition** assigns a single numerical relationship between two variables (length is 2½ times width). This is the most difficult kind of assignment.
3. The **question proposition** assigns a single numerical value for some variable (how much time it takes to empty a tank).

Completing and assigning values to these propositions results in distinct conceptual models for each type of problem (Mayer, 1982). To build models of problems, learners must construct some kind of semantic network depiction of the problem, such as that in Figure 15.1.

Each subject-matter domain has distinct models for different types of problems. These models may include the same sets or propositions but interrelate them differently. For example, different motion problems use the same sets but assign them to different propositions (Mayer, Larkin, & Kadane, 1984). An *overtake* problem (one vehicle starts and is followed later by a second that travels over the same route at a faster rate) possesses a propositional structure that includes,

(rate for A) =
(rate for B) =
(time for A and B) =
(time for B to overtake A) = unknown

A closure problem (two vehicles start at different points traveling toward one another), however, possesses a propositional structure that includes:

(rate for A) =
(rate for B) =
(distance between A and B) =
(time) = unknown

It is essential that students understand these propositions and the relations between them and construct a conceptual model of the problem structure. Based on the similarity of conceptual models, story problems in different domains share characteristics. When they do, they belong to the same class of problems.

Classifying problem types is essential to an understanding and transfer of problem solving (Mayer et al., 1984). Why? Because novices tend to classify problems based on their surface content, resulting in a miscategorization of the problem type based on its structural characteristics (Blessing & Ross, 1996). Mayer et al. (1984) found that when learners miscategorize problems, they more frequently commit errors.

The importance of problem classification has led many researchers to work on problem typologies. As pointed out before, Riley et al. (1983) began the process of problem classification in elementary mathematics story problems by identifying change, compare, and combine problems that vary by location of the unknown in the problem structure (initial value, the change value, or the result). Marshall (1995) expanded that list of simple math story problems to include change, group, compare, restate, and vary problems. Change problems present a quantity that changes over time. In group problems, small groups are combined into larger groups. Compare problems contrast two things to determine which is larger and which is smaller. Restate problems link things in relational terms (twice as big) and then restate that relationship in terms of numerical values. Finally, vary problems state a relationship between two things and generalize that relationship to new situations. The problem typologies of Riley et al. and of Marshall are both concerned with the location of the unknown in the problem.

While studying problem categorization of physics problems, Chi, Feltovich, and Glaser (1981) also found that experienced solvers relied more on conceptual models of the problems' structural characteristics than the quantitative models represented in formulas. They identified several categories of physics problems, including:

- Newton's second law;
- conservation of energy/work–energy;
- conservation of momentum;
- angular motion;
- rotational motion, kinematics, and dynamics;
- circular motion;
- center of mass;
- statics, including conservation of angular momentum and work problems;
- linear kinematics;
- vectors;
- springs (potential energy and force).

A more elaborate typology was produced for algebra problems. Mayer (1982) analyzed thousands of problems in numerous high-school algebra books for their structural similarities. He identified eight families of story problems:

1. amount per time rate;
2. unit cost rate;

3. percent cost rate;
4. straight rate;
5. geometry (simple area);
6. physics (Ohm's law);
7. statistics (combinations);
8. number story.

Within each family of story problems, Mayer (1982) identified categories of problems. For example, in amount-per-time-rate problems, he identified motion problems, current problems, and work problems. Under each of these categories, he identified problem templates that share similar problem characteristics. For example, under motion problems, he identified templates such as overtake, opposite direction, round trip, closure, speed change, same direction, and so on. The structure for motion-overtake problems specifies that "one vehicle starts and is followed later by a second vehicle that travels over the same route at a faster rate" (Mayer, 1982, p. 156). Variables include rate for A, rate for B, time for A and B, and time for B to overtake A. The fact that problem typologies such as these exist for so few domains indicates the traditional lack of importance accorded to problem-schema construction while solving story problems. Getting the right answer seems to be more important to many teachers than understanding the nature of the problem.

What Situational Properties Are Important in Problem Schemas?

Students also associate situational characteristics depicted in the story with the structural characteristics of a problem contained in students' conceptual models of story problems (Kintsch & van Dijk, 1978). Although the structure of the propositions in the problem is a coherent representation of the problem's macrostructure (to use Kintsch's term), the situational characteristics represent the contextual story elements in the problem. For example, a propositional structure relying on distance, rate, and time equations may have a variety of situational characteristics including boats, trains, planes, or automobiles moving in the same direction, opposite directions, or round trips. The situational characteristics are included in the students' representation of the problem in their conceptual model (Briars & Larkin, 1984).

Structural and situational characteristics are complementary. However, novice problem solvers tend to classify problems based on the situational characteristics of problems, and experienced solvers categorize problems based on structural characteristics (Chi et al., 1981; Silver, 1981). Naive problem solvers tend to think of problems only in situational terms (Rogoff & Lave, 1984), often missing the conceptual structure that defines the problem class. Novice problem solvers categorize physics problems based on surface level or situational attributes, while experts categorize based on the structural attributes (Snyder, 2000). For example, novices will classify all problems that contain cars, roads, inclines, surfaces, and slopes together, despite that they may represent theoretically different kinds of problems. On the other hand, more advanced learners who focus only on the structural characteristics of a problem often produce answers that are situationally impossible (Hinsley, Hayes, & Simon, 1977). Students rarely reconcile the situational and structural characteristics in their conceptual-models problems. For example, freshmen chemistry students who practiced categorizing problems based on structural characteristics had higher achievement in more complex problem-solving situations, but that achievement was not linked to conceptual understanding (Bunce, Gabel, & Samuel, 1991).

Although many psychologists believe that the situational characteristics of the problem only distract learners from understanding the structural nature of the problem, others believe that effective problem solvers make sense of the quantitative constraints in a problem based on the situational characteristics (Briars & Larkin, 1984). Nathan, Kintsch, and Young (1992) showed that integrating structural and situational characteristics and animating the situational representations produced the highest problem-solving performance. They tested a computer-based environment known as ANIMATE and found that the student's conceptual model of the problem (problem schema) contained both a structural model and a situational model of the problem. For example, compound motion and work problems have similar events such as traveling in opposite directions, walking together, or riding a bus with output and time as the basic dimensions that organize the story. Students make constructive inferences in constructing their conceptual models based on situational characteristics of the problem. By providing an animated representation of the situational model of the problem, students learn to associate situations with formal expressions and to enhance problem comprehension.

So, the most successful problem solvers are those who can integrate the situational and structural characteristics of the story problems. Blessing and Ross (1996) showed positive effects of situational content on problem solving and problem classification of experienced problem solvers (college students). Even experienced problem solvers have knowledge about problem types that is sensitive to content, and situational content is available quickly, allowing experienced problem solvers to activate conceptual models of problem types that include solution procedures. Even experts often base their initial categorizations on problem's surface content (Novick, 1988).

Perhaps the most important role played by the situational characteristics of story problems is to anchor the problem to the everyday world, that is, to provide context to enhance meaning-making by problem solvers. Despite the fact that students often do not take story problems seriously because "an otherwise boring task cannot be made interesting by adding a few interesting details" (Mayer, 1998, p. 57), the situational details are too often the primary components providing meaning to the problem. It is likely that the simplicity of the story contexts and their lack of relevance to learners' interests and backgrounds are responsible for the lack of interest, according to Mayer. The Jasper Series of video-based story problems (described in Chapter 8), on the other hand, has been shown to successfully engage students in complex mathematical problem solving and transfer (Cognition and Technology Group at Vanderbilt, 1997), in large part because of the narrative complexity and the video medium. The narrative anchor is essential to ownership and engagement in the problem solving.

WHAT CONSTITUTES A PROBLEM SCHEMA?

As just presented, problem schemas consist of structural and situational characteristics. In this book, I consistently argue for deeper conceptual understanding and representation of problems. A robust schema for problems includes multiple, synergistic representations. In Chapter 4, I describe a model for the systems being troubleshot. This model also serves as a useful model for problem schemas. The topographic and pictorial layers represent the situational characteristics of a problem. Constraining these situational characteristics is information about the normal states or problem elements. What are the normal states or values for each component in a problem? Problems are often solved by recognizing that a problem element is out of bounds, that is, out of the normal range of operations. Those states often manifest themselves in symptoms. For example, when diagnosing a patient, a white-blood-cell count that exceeds normal levels provides an important symptom in the diagnosis. Associated with these symptoms is knowledge about the probability of a state being out of bounds. The probability overlay conveys probabilities of malfunctions or fault states. Being able to match existing symptoms and probabilities with a set of stored symptoms and probable fault states represents a common approach to fault finding (Patrick, 1993).

Robust problem schemas also possess a variety of structural characteristics. Not only do problem solvers need to know what elements exist in the problem but they also need to know how those elements affect each other. That is, what are the structural relationships among the problem elements. The most important relationships are causal (see Chapter 17).

Problem schemas also possess knowledge about the process of solving problems. I have argued throughout the book that traditional methods for teaching problem solving overemphasize the procedure for solving the problem, ignoring both the conceptual components but also other aspects of the process dimension of problem schemas. Problem-solving processes should also emphasize strategies for when and where to apply different procedures as well as the actions that are required to solve the problem.

The implications of this enriched conception of problem schemas are obvious. Problem-solving instruction must be extended to include these other dimensions of the problem. That will require deeper understanding of the problems being taught as well as more time and effort expended during instruction. These additional requirements are problematic, but if we expect students to understand the problems they are solving and be able to transfer the skills required to solve them, then we must make the effort.

HOW DO WE ENHANCE THE CONSTRUCTION OF PROBLEM SCHEMAS?

Learners are expected to construct (induce) schemas from the cases as examples, analogues, alternative perspectives, or student-constructed cases (see Chapters 8–14); to store the schemas in memory; and later analogically to transfer to them when solving new problems (Gick & Holyoak, 1983). The transfer is a form of concept generalization, that is, generalizing one problem concept (schema) to another. Generalization from problem-solving examples may automatically occur in limited ways (Catrambone & Holyoak, 1989); however, knowledge generalization is not a natural consequence of reasoning by analogy (Didierjean, 2003). Learners sometimes adapt highly specific, contextualized knowledge from analysis of examples without engaging in the reasoning-by-analogy process that leads to generalization. Attracting attention to the similarity between problems improves generalization during problem solving (Didierjean, 2003).

In order to construct problem schemas and to transfer problem solutions, students must induce a conceptual model (schema) for the kind of problem being solved. The most successful methods for teaching problem solving support student construction of problem schemas (Taconis, Fergusson-Hessler, & Broekkamp, 2001), because it is the quality of students' conceptual model that most influences the ease and accuracy with which problems can be solved (Hayes & Simon, 1976). To solve problems consistently, learners must demonstrate conceptual understanding of the problems by constructing problem schemas for each kind of problem (e.g., conservation of momentum, angular motion, or kinematics in physics) that includes semantic and situational information about the problem that is associated with the procedures for solving that type of problem (Reusser, 1993).

In the remainder of this chapter, I describe methods for focusing students' attention on problem-schema construction. These methods have been shown to enhance the induction or construction of robust problem schemas. In order to ensure that learners are constructing appropriate schemas, it is necessary to analyze the underlying structure of each case (example, experience, analogue, or perspective) to ensure that they are structurally congruent. When analyzing cases, the surface features that too often attract the attention of poor problem solvers must be identified and set aside. The focus of the analysis should be on the higher-order, structural relationships in each case.

What Are Structure Maps and How Do They Help Students?

Categories of problems in well-structured disciplines such as physics possess a finite number of possible problem elements that are interrelated. Each pair or combination of elements represents a proposition. According to structure-mapping theory (Gentner, 1983), attributes of a concept are predicates taking one argument and relationships are predicates taking two or more arguments. The relationships (second-order predicates) that define most problems are causal (Jonassen & Ionas, 2008). Figure 15.2 illustrates all of the propositions commonly found in work–energy problems in physics. We have used this structure to instruct students in physics classes. The purpose of structure maps is to provide a tool for enabling students to analyze problems. All work–energy problems contain some combination of the predicates in Figure 15.2, so the job of the student is to analyze problems to see which elements are included.

Structure maps can be used by students in a variety of ways. The most obvious method is to require students to analyze problems

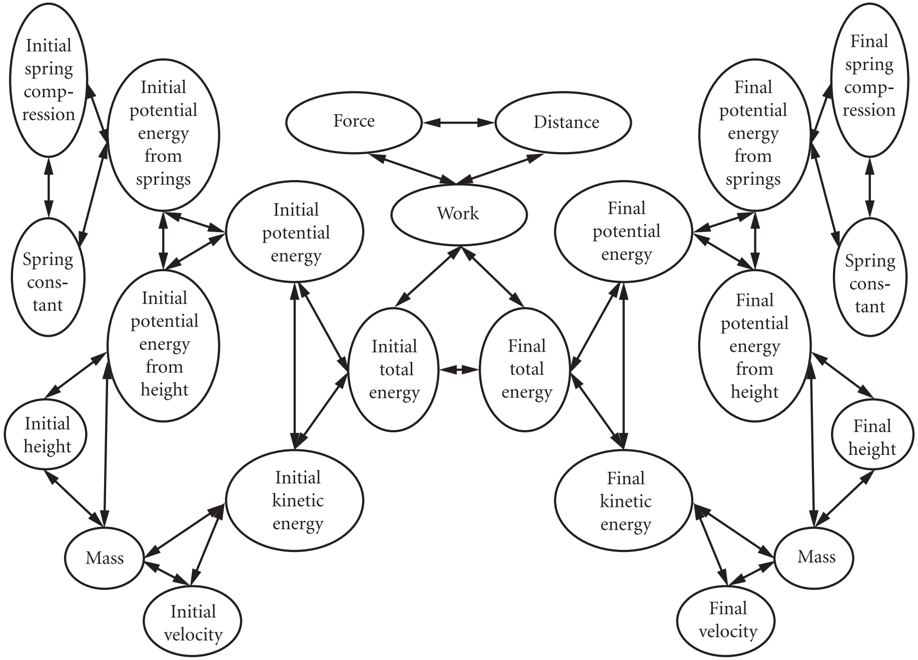
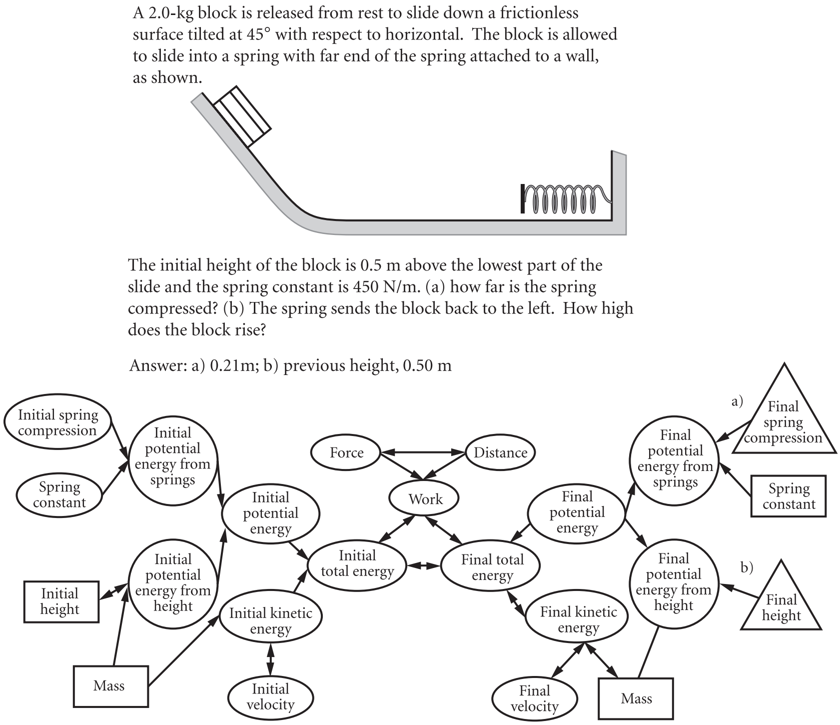


Figure 15.2 Structure map of work–energy problems.

in terms of the structure maps, in addition to solving the problems quantitatively. Doing that obviously requires that students first learn the symbol system of structure maps, which is difficult and unnatural for students familiar only with equations. Figure 15.3 illustrates all of the components that may be presented in a work–energy problem. Students identified quantities that are explicitly given in the problem as green rectangles, quantities that are not given but can be assumed as red rectangles, quantities that are unknown and asked for in the problem as red triangles, and intermediate quantities that need to be calculated along the way to solving for the unknown from those that are given and assumed as circles. This kind of analysis focuses student attention on the conceptual elements in the problem. Students could also be required to conceptually describe the nature of the relationship between any of those quantities in the problem. What is the relationship between initial potential energy and final kinetic energy?



A 2.0-kg block is released from rest to slide down a frictionless surface tilted at 45° with respect to horizontal. The block is allowed to slide into a spring with far end of the spring attached to a wall, as shown.

The initial height of the block is 0.5 m above the lowest part of the slide and the spring constant is 450 N/m. (a) how far is the spring compressed? (b) The spring sends the block back to the left. How high does the block rise?

Answer: a) 0.21m; b) previous height, 0.50 m

Figure 15.3 Using structure map to analyze problems.

How Can You Question Students About Structural Relationships?

As described in Chapter 18, questioning is one of the most fundamental approaches to guiding human reasoning so they are essential to the problem-solving process. In order to solve problems, it is important that learners acquire the skills and strategies of question answering as well as question asking. In addition to asking students to answer questions quantitatively, students should be required to answer and explain conceptual questions about problems they solve. For example, for the physics problem in Figure 15.3, the following questions might be asked (see Table 15.1). In addition to answering the multiple-choice question, students should be able to explain why they answered as they did (an implicit form of argumentation).

What Is Text Editing and How Does It Help Students?

Text editing is a method (described also in Chapter 22) for assessing the quality of problem schemas. Text editing questions (Low & Over, 1989; Low, Over, Doolan, & Michell, 1994; Ngu, Lowe, & Sweller, 2002) present standard questions such as that in Figure 15.4 to which a quantity has been added or deleted or left alone. Students are required to identify whether the problem contains sufficient, irrelevant, or missing information. Students cannot answer such questions unless they understand what kind of problem it is and what elements are appropriate for that kind of problem. While they appear fairly simple, these questions are difficult for students to answer, especially if the students are required to explain their answers.

How Do We Help Students to Classify Problems?

Other methods for eliciting understanding of problem schemas require students to classify or to sort problems. One of these methods is to present pairs of problems and to ask learners to identify on a scale how similar the problems are (Littlefield & Rieser, 1993; Low & Over, 1989, 1990, 1992).

Another method is to present a problem and to ask students to classify the type of problem, as, for example, kinematics, Newton's second law, work–energy, etc. (Chi et al., 1981). Science courses are normally taught as a sequence of problem types, so the first week (typically kinematics), you would ask, "Is this a kinematics problem or not?". For Week 2 (work–energy, for example), as which of the two types (kinematics or work–energy). Each week, you add another problem type.

Table 15.1
Question prompts focusing on problem schemas

Which of the following quantities are directly given/stated in the problem? (Select all that apply):

- initial gravitational potential energy of the block
- friction of the surface
- mass of the block
- forces on the block at initial position
- spring constant
- angle of the slope with respect to horizontal.

Identify the nonconservative forces acting on the block during the process described in the problem (if any).

- friction
- gravity
- spring force
- friction, gravity and spring force

There are no nonconservative forces acting on the block that are taken into account. In terms of conservation of its mechanical energy, the system is described as:

- conservative system (mechanical energy conserved)
- nonconservative system

In general, this problem could be solved by applying (select all that apply):

- Newton's second law of motion
- work–energy theorem
- conservation of mechanical energy
- conservation of linear momentum

Initial energy of this system consists of the following energies (select all that apply):

- gravitational potential energy
- kinetic energy of the block
- spring potential energy

During the full process described in the problem, which forms of energy change (select all that apply)?

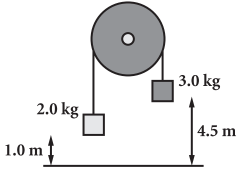
- gravitational potential energy
- kinetic energy of the block
- spring potential energy

Another, quite similar, task is to present a selection of problems and to ask the students to sort them into groups. You ask students to explain the groups in terms of physics concepts and principles.

Problem-classification exercises are useful for helping students to construct more robust problem schemas, because students tend to

You are given a problem below.

A 2.0 kg mass initially 1.0 m above the ground is attached to thin cord that passes over a frictionless pulley to a second 3.0 kg mass which is initially 4.5 m above the ground. Both masses are initially at rest. Find the final velocity of the 3.0 kg mass right before it hits the ground.



In the problem statement above, specify which, if any, of the following quantities are *not* relevant for solving the problem.

(a) 2.0 kg mass (b) 3.0 kg mass (c) 4.5 meters (d) 1.0 meters

(e) None of the above. You need all the information given to solve the problem.

Figure 15.4 Text editing question to support problem schema development.

generalize problem schemas based on surface level similarities among problems (Chi et al., 1981; Dufresne, Gerace, Hardiman, & Mestre, 1992; Hardiman, Dufresne, & Mestre, 1989). Therefore, any efforts to help them understand the structural, rather than surface, characteristics of problems will enhance students' problem-schema development. In Chapter 2, I showed that students seldom construct robust schemas when they plug values into equations and solve the equation in order to derive the correct answer.

What Is Analogical Encoding?

Another powerful method for supporting problem-schema development is analogical encoding where students compare and contrast pairs of problems for structural similarity. Analogical encoding is more completely described in Chapter 16.

ARE PROBLEM SCHEMAS POSSIBLE FOR ALL KINDS OF PROBLEMS?

Developing problem schemas is an important part of solving well-structured problems. Constructing models for each kind of problem being solved enables problem solvers to apply a set of procedures for solving the problem more efficiently. Constructing and applying problem schemas is also known as problem finding, problem definition, and problem sensing.

Most of the research on problem schemas has been conducted with well-structured problems in well-structured disciplines, such as physics. That is because well-structured problems have constrained problem definitions with well-defined set of attributes. Because ill-structured problems do not have known solutions or solution methods, their attributes or characteristics vary, so it may be difficult or impossible to identify a kind of problem with variable attributes. This does not mean that ill-structured problems cannot be identified as similar to other problems solved. They often are. The similarity is based on previously experienced problems, which is described in detail in Chapter 12.

16

ANALOGICALLY COMPARING PROBLEMS

In order to teach students how to solve problems, instructors most often demonstrate how to solve a problem using procedures and equations and then ask learners to apply that method to solve a new transfer problem. Transferring learning how to solve a problem from a single example to a new problem requires that learners induce a schema for that kind of problem from that single example and then apply that schema to a new, contextually varied problem (see Chapter 15 for more detail on problem schemas and Chapter 9 for more detail on worked examples). This single-example approach to teaching problem solving usually results in students imitating the process for solving the problem while ignoring the structural characteristics of the problem. As a result, when asked what kind of problem they are solving or transferring the solution methods varied problems, student fail. They fail for three reasons:

1. over-reliance on a single form of problem representation;
2. student conceptions of problems are based on surface level characteristics of the problem;
3. over-reliance on a single example or analogue. Over-reliance on a single example also results in failure to understand basic concepts during instruction as well.

In almost every class, instructors rely on only a single form of problem representation. In math and science classes, instructors write an equation on the board and then teach students how to derive the correct, quantitative answer (see Chapter 2 for more detail on solving story problems in mathematics and the sciences). Mathematics problems employ three different symbol systems (symbolic, graphic, and table) as well as verbal representations. It is important for mathematics problems to be represented in all three ways in order to comprehend the problem structure. Yet, math curricula typically are organized so there is almost no contact between the symbol systems and students are given no opportunity to learn to switch between them. This overreliance on a quantitative representation of the problem implies that solving problems is a procedure to be memorized, practiced, and habituated and that emphasizes answer getting not meaning making (Wilson, Fernandez, & Hadaway, 2001). When students directly translate the key propositions in the problem statement into a set of computations, they more frequently commit errors, because problem solving requires the capacity to recognize the deep structure of the problem (Lucangeli, Tressoldi, & Cendron, 1998). Understanding the deep structure of a problem relies on qualitative (semantic) representation of the problem (see Chapter 15 for more detail on problem schemas). However, the qualitative and quantitative representations are complementary and both necessary for problem-solving transfer. According to Ploetzner, Fehse, Kneser, & Spada (1999), qualitative problem representations are necessary prerequisites to learning quantitative representations. When students try to understand a problem in only one way, especially when that way conveys no conceptual information about the problem, students do not understand the underlying concepts they are working with.

A second difficulty in generalizing schemas during transfer is the tendency of students to generalize problem solutions based on surface-level similarities among problems (Chi, Feltovich, & Glaser, 1981; Dufresne, Gerace, Hardiman, & Mestre, 1992; Hardiman, Dufresne, & Mestre, 1989; Schoenfeld & Herrmann, 1982). Because they are taught with only quantitative problem representations, students do not learn about the deep-level structural characteristics. Loewenstein, Thompson, and Gentner (1999) showed minimal transfer from a single example. Unfortunately, transfer from a single problem is insufficient for schema induction.

A third impediment to schema generalization is the overuse of single analogies during instruction. The most common form of problem-solving instruction is the demonstration of a single problem followed by a practice problem. Traditional approaches to problem-solving instruction assume that people can abstract schemas from single examples and apply them to transfer problems. Loewenstein et al. (1999) showed minimal transfer from a single example. Unfortunately, transfer from a single problem is insufficient for schema induction. However, over two decades of research has confirmed an advantage for comparing two cases over studying examples separately, a process known as analogical encoding (described next).

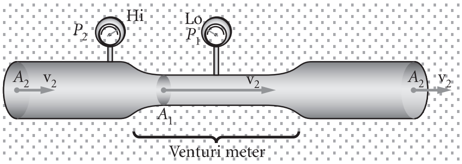
WHY SHOULD LEARNERS ANALOGICALLY COMPARE MULTIPLE PROBLEMS?

Problem-solving transfer is based on schema induction and reuse, which is a form of analogical reasoning. That is, in order to learn to solve a new problem, students should analogically compare that problem to a structurally similar problem. In Chapter 11, I described cases as analogies. In this chapter, I describe the cognitive process for comparing analogies. Although these chapters appear redundant, they each emphasize a different aspect of analogical reasoning.

Extensive research by Gentner and her colleagues has shown that comprehension and schema induction is greatly enhanced by analogical encoding, where learners compare two analogues for their structural alignment in order to induce a more abstract problem schema. Analogical encoding is the process of mapping structural properties between multiple analogues, typically pairs. Rather than attempting to induce and transfer a schema based on a single example, Gentner and her colleagues have shown that comprehension, schema induction, and long-term transfer across contexts can be greatly facilitated by comparing two analogues for structural alignment (Catrambone & Holyoak, 1989; Gentner & Markman, 1997; Gentner & Markman, 2005; Loewenstein et al., 1999; Loewenstein, Thompson, & Gentner, 2003). When learners directly compare two examples, they can focus on structural similarities, but if presented with just one example, they are far more likely to recall examples based on surface features. Analogical encoding fosters learning because analogies promote attention to structural commonalities, including common principles and schemas (Gick & Holyoak, 1983). Experts, for example, are better at recalling examples based on structural commonalities because they better understand those structural commonalities (Dunbar, 2001). Comparing analogies, rather than trying to apply a single analogy to a target problem leads to better schema abstraction and transfer (Gentner, Loewenstein, & Thompson, 2003). For example, Figure 16.1 illustrates one of many pairs of fluid problems that we tested in a physics class. Although these problems look different, they are structurally congruent. Students were directed to compare the problems for similarities and differences. Although quantitative performance was not improved, practice in

PROBLEM 1

A Venturi meter is a device for measuring the speed of a fluid within a pipe. The drawing shows a gas flowing at speed v_2 through a horizontal section of pipe whose cross-sectional area is $A_2 = 0.0700\ m^2$. The gas has a density of rho = 1.30 kg / m^3. The Venturi meter has a cross-sectional area of $A_1 = 0.0500\ m^2$ and has been substituted for a section of the larger pipe. The pressure difference between the two sections is $P_1 - P_2 = 120$ Pa. Find the speed v_2 of the gas in the larger original pipe.



PROBLEM 2

The water tower in the drawing is drained by a pipe that extends to the ground. The flow is nonviscous. What is the absolute pressure at point 1 when the valve is opened and the water is flowing? Assume that the water speed at point 2 is negligible and that the top surface of the water at point 2 is at atmospheric pressure $P_{atm} = 1.013 \times 10^5$ Pa. The density of water is rho = 1,000 kg/m^3, and the acceleration of gravity is g = 9.80 m/s^2.

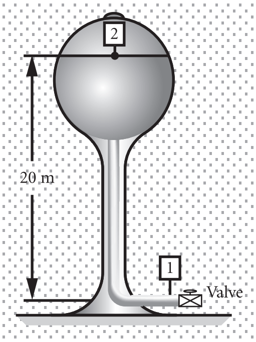


Figure 16.1 Pair of physics problems to be analogically compared.

analogical encoding significantly predicted performance on the conceptual questions during exams (Jonassen, Cho, & Wexler, 2008).

The theoretical rationale for analogical encoding is structure-mapping theory (Gentner, 1983, 1989). Structure-mapping theory describes the process of structural alignment, that is, the setting up of correspondences between structured representational elements in two domains and transferring information guided by common relational structure (Kurtz, Miao, & Gentner, 2001). How does this work? Domains and situations are psychologically viewed as objects, the attributes of those objects, and the relations between those objects. Consistent with semantic network theory (Quillian, 1968), knowledge in human memory can be represented as propositional networks of nodes and predicates. As described in Chapter 15, attributes are predicates taking one argument (a concept), and relationships are predicates taking two or more arguments (a proposition). The rules that define those relationships depend only on syntactic properties of knowledge representation and not on specific content of domains, allowing analogies to be distinguished clearly from literal similarity (Gentner, 1983). The syntactic relations are determined by systematicity (existence of higher-order relations).

Analogical encoding is a method that facilitates that structural mapping. In order for analogues to be structurally aligned,

- alignment must be structurally consistent (matching relations must have matching arguments and one-to-one correspondence);
- the relational focus must involve common relations but not necessarily common objects;
- analogies match connected systems of relations.

(Gentner & Markman, 1997).

Despite the consistent results from analogical encoding research, there remain unresolved issues.

WHAT DON'T WE KNOW ABOUT ANALOGICAL ENCODING?

The first unresolved issue in analogical encoding relates to the complexity and domain dependence of analogues. Nearly all of the analogical-encoding research has required learners to map relatively simple, context-independent problems (e.g., Duncker's X-ray problem) to test their assumptions (Cummins, 1991). Some analogical encoding research has focused on real-world negotiation problems (Gentner et al., 2003; Loewenstein et al., 1999, 2003); however, those problems focused on a limited number of structural comparisons among analogues. Analogical encoding research has been very successful in part because mapping structural elements between simpler problems requires fewer cognitive resources. With more complex problems, structural alignment will be more difficult, especially given the tendency among students to compare problems based on surface features of the problem. Analogical encoding has not been applied to complex and ill-structured problems. Why is that important? Because the use of analogies is guided by three types of constraints:

1. structural similarity of key relations between objects;
2. structural parallels between the roles in the source;
3. target domains, and purpose (what analogy is intended to achieve).

(Holyoak & Thagard, 1997)

Although analogical encoding has been consistently shown to facilitate schema induction and transfer, the purpose of the experimental subjects has rarely been to learn how to solve complex domain-specific problems.

A limited body of research has examined methods for facilitating analogical encoding. In order to support that comparison process, different studies examined the physical juxtaposition of cases (Kotovsky & Gentner, 1996), using software (Kolodner, 1993), similarity ratings (Markman & Gentner, 1993), directed questions (Catrambone & Holyoak, 1989), describe commonalities (Gick & Holyoak, 1983), and joint interpretation and alignment (Kurtz et al., 2001). Gentner et al. (2003) provided a definition of the key principle to be transferred (trade-off or contingent contract). They also required learners to complete a diagram, resulting in a 90% transfer rate. An important factor in analogical encoding is the depth of the comparison process. Kurtz et al. (2001) compared treatments requiring participants to specify differences between two pictured scenarios to write scenario descriptions, and to rate the similarity of scenarios. They found that making explicit comparisons (mutual alignment of the analogues) promotes greater comprehension of common causal structure, but only when the comparison is intensive.

HOW DO WE FACILITATE ANALOGICAL ENCODING?

Another unresolved issue in analogical encoding research is the likelihood that learners will actually engage in analogical comparisons and how to facilitate them if they do not. Loewenstein et al. (1999) showed that comparing (analogical encoding) cases is not automatic. Spencer and Weisberg (1996) found that presentation of multiple source analogies is not sufficient to ensure transfer across contexts. Instruction to support analogical encoding is necessary. Merely reading or receiving multiple cases is not enough to produce comparison effects (Loewenstein et al., 1999). In order to support that comparison process, intensive structural comparisons must be made. In order to accomplish that, instructional support of analogical encoding is necessary. Lowenstein et al. (1999) found that making relational structure explicit during encoding promotes appropriate transfer, and comparing the structural alignment highlights appropriate similarities between the analogues. Given the well-established tendencies of learners to compare problems based on surface similarities (attribute relationships), instruction should be designed to emphasize those structural relationships so that learners compare and contrast those structural properties. “A fruitful avenue of research may involve searching for ways of helping learners to focus on relevant features of training examples in a variety of domains and to learn to reliably identify these features in transfer problems (Catrambone & Holyoak, 1989, p. 1154).

How Can Questioning Help Learners to Analogically Compare Problems?

As described in Chapter 18, questioning is one of the most fundamental cognitive components that guide human reasoning (Graesser, Baggett, & Williams, 1996). Humans reason by asking questions and interpreting answers, especially when learners generate and answer questions requiring explanatory reasoning (Graesser, Baggett, et al., 1996). Our goal should be to help students to ask and answer deep-reasoning questions. That is, the question-answer rhetorical structure is the most common dialogue pattern in naturalistic conversation (Graesser, Swamer, Baggett, & Sell, 1996).

In this chapter, questions are used to direct students' attention to structural characteristics of problem pairs. The goal of the questions is to get students to compare structurally similar pairs of problems or to contrast structurally dissimilar pairs of problems. In a series of studies, we examined the use of questions to focus students' attention on structural similarities between pairs of problems. Figure 16.2 shows how questions were used to help electrical-engineering students compare structurally similar problems. Beware that these kinds of questions are incongruent with the kinds of right–wrong questions that most students are inured to, so practice in answering such questions is necessary. Also, explanatory feedback to students will help them to better understand the structural relationships that you are trying to emphasize.

How Can Structure Mapping Help Learners to Analogically Compare Problems?

As shown in Chapter 15, one method for helping students to construct problem schemas is to provide structure maps for each identifiable kind of problem. Structure maps illustrate all of the potential elements and structural relationships.

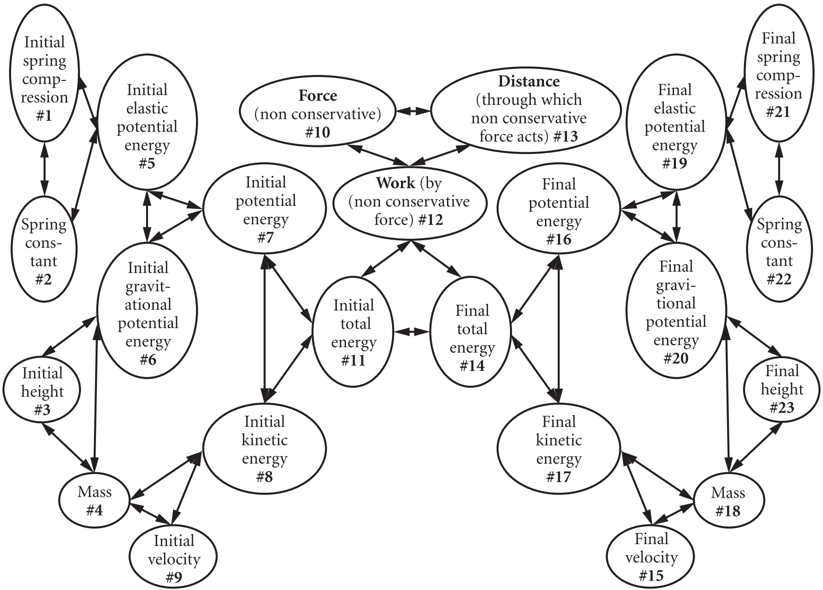
For the structure-mapping treatment, we constructed a map showing functional relationships among those elements for a specific class of problem. Questions can also be used to prompt student attention to those elements and relationships. The goal is for students to identify those elements and relationships in pairs of problems. Students are shown the map along with the problem pairs and required to compare the values in embedded in the problem to the map (see Figure 16.3).

Problem A: The electron concentration in silicon decreases linearly from 10^{16} cm^2 to 10^{15} cm^2 over a distance of 0.10 cm. The cross sectional area of the sample is 0.05 cm^2. The electron diffusion coefficient is 25 cm^2/s. Calculate the electron diffusion current.	**Problem B:** The whole concentration in p-type GaAs is given by p=10^{16} (1=x/L)cm^2 for 0≤x≤L where L=10 μm. The hole diffusion coefficient is 10 cm^2/s. Calculate the hole diffusion current density at (a) x=0, (b) x=5 μm, and (c) x=10 μm.
Problem A: What laws are needed to solve this problem? Select all that apply. 1. Ohm's law 2. Current density theorem 3. Hall effect 4. Einstein's relation 5. Laws of carrier diffusion	Problem B: What laws are needed to solve this problem? Select all that apply. 1. Ohm's law 2. Current density theorem 3. Hall effect 4. Einstein's relation 5. Laws of carrier diffusion
Problem A: What is needed to solve this problem? Select all that apply. 1. Resistance 2. Conductivity 3. Dopant concentration 4. Carrier mobility 5. Sample length 6. Temperature	Problem B: What is needed to solve this problem? Select all that apply. 1. Resistance 2. Conductivity 3. Dopant concentration 4. Carrier mobility 5. Sample length 6. Temperature
Problem A: Which of the following quantities is directly given from the problem? Select all that apply. 1. Area 2. Volume 3. Doping type 4. Electric field 5. Mobility	Problem B: Which of the following quantities is directly given from the problem? Select all that apply. 1. Area 2. Volume 3. Doping type 4. Electric field 5. Mobility
Problem A is changed so that the carrier concentration has changed to holes. What additional information would enable you to find the hole diffusion current? Select all that apply. 1. Current density 2. Drift velocity 3. Hole mobility 4. Hole diffusion coefficient 5. None of the above—you already have sufficient information	Problem B is changed so that the carrier concentration has changed to electrons. What additional information would enable you to find the electron diffusion current? Select all that apply. 1. Current density 2. Drift velocity 3. Hole mobility 4. Hole diffusion coefficient 5. None of the above—you already have sufficient information

Figure 16.2 Questions directing students to structural comparisons between problems.

What Other Methods Have Been Used to Help Learner Analogically Compare Problems?

Numerous generative strategies for enhancing analogical transfer between cases have been tried. Gick and Holyoak (1983) attempted to foster the abstraction of a problem schema from a single story analogy



Work–Energy Problems

Problem1 A 0.088 kg arrow is fired from a bow whose string exerts an average force of 110N over a distance of 0.78 m. Neglecting air resistance, what is the speed of the arrow as it leaves the bow?	Problem2 A 0.25 kg softball is pitched at 26 m/s. By the time it reaches the plate a distance 15m away it has slowed to 23 m/s. Neglecting gravity, what is the average force of air resistance during the pitch?
Q1.1 What part(s) of the structure map is/are best representative of "A 0.088 kg arrow is fired from a bow"?	Q2.1 What part(s) of the structure map is/are best representative of "A 0.25 kg softball is pitched"?
Q1.2 What part(s) of the structure map is/are best representative of "string exerts an average force of 110 N"?	Q2.2 What part(s) of the structure map is/are best representative of "pitched at 26 m/s"?
Q1.3 What part(s) of the structure map is/are best representative of "over a distance of 0.78m."?	Q2.3 What part(s) of the structure map is/are best representative of "by the time is reaches the plate a distance 15m away"?
Q1.4 What part(s) of the structure map is/are best representative of "what is the speed of the arrow as it leaves the bow?"?	Q2.4 What part(s) of the structure map is/are best representative of "it has slowed to 23 m/s"?
Q1.5 Choose all parts of the structure map you believe are necessary for solving this problem.	Q2.5 What part(s) of the structure map is/are best representative of "what is the average force of air resistance during the pitch?"?

Figure 16.3 Questions involving a structure map to focus attention on structural characteristics of problems.

by means of summarization instructions, where students constructed a verbal statement depicting the underlying principle or a diagrammatic representation of it. Reed (1987) had students rate the potential usefulness of solutions for pairs of problems that were equivalent (same story, same procedure), similar (same story, different procedure), isomorphic (different story, same procedure), or unrelated (different story, different procedure). Merrienboer and Croock (1992) presented examples that contained gaps that had to be closed. Reimann & Schult (1996) recommend memory assistants that remind students during problem solving of relevant problems they have solved before and point out differences between the current problem and the previous problem (see Chapter 12 about cases as prior experiences). None of these devices achieved a notable degree of success. Probably the most effective strategy that has been tested is analogical encoding (Gentner et al., 2003). Analogical encoding requires drawing comparisons across examples, when learners compare and contrast two examples in order to determine the structure that is common to both, leading to structural alignment. Gentner et al. (2003) found that learners who compared two cases developed better schemas than those studying separately and were better able to transfer the principles to new cases. Schema abstraction and transfer is related to degree of effort in the comparison process.

Some researchers have examined the effectiveness of monitoring and self-explanation training (Chi, deLeeuw, Chiu, & LaVancher, 1994). Chi, Bassock, Lewis, Reiman, and Glaser (1989) found that higher-achieving students naturally generate self-explanations by expanding their solutions to other problems and monitoring their own understanding and misunderstanding. Renkl, Stark, Gruber, and Mandl (1998) found that self-explanations improved near transfer and far transfer of problem solving. Understandably, the quality of the self-explanation best predicted the ability to transfer. Self-explanations occur naturally among learners and have some positive effects on transfer.

The goal of analogical problem solving is the extraction from analogous (source) case(s) the conceptual structure of the problem and the application of that structure to a new problem. The methods described in this chapter may help students to better understand the kinds of problems they are solving by comparing structurally congruent problem pairs.

17

UNDERSTANDING CAUSAL RELATIONSHIPS IN PROBLEMS

As described in Chapter 15, concepts (schemas) are the bases of human understanding and reasoning. Concepts mentally represent things in the world. Concept categorization is the most pervasive cognitive process in everyday life (Rehder, 2003) as we access terms to describe what we are thinking or interpret what others say to us. Except for identifying instances of a concept, they are rarely accessed or applied individually. Rather, most forms of understanding require humans to associate combinations of concepts into relationships between concepts (Jonassen, 2006b).

The most common type of conceptual relationship that underlies all thinking is causal (Carey, 2002; Keil, 1989). Causal propositions include a set of conditions and a set of effects or consequences that are connected by a causal relationship. Causal relationships are examples of what Gagné (1965) referred to as principles; however, not all of Gagné's principles were causal. For example, we are all aware that applying force to the accelerator in our cars (causal condition or agent) results in the car accelerating (causal event or effect). If our goal is to learn how automobiles function, however, that proposition is oversimplified. So we must learn the complex causal propositions that describe the causal relationships among the accelerator cable or receiver, computer, fuel injectors, pistons, transmission, wheel rotation, and so on. The ability to reason from any set of concepts depends on the viability of the propositions that are formed by combinations of concepts (Jonassen, 2006b). Understanding a problem requires that learners understand the structural representation of causal propositions in the problem. Causal maps, as I will illustrate later in the chapter, are alternative representations to the logical structure maps of problems discussed in Chapter 15 and 16. In Chapter 4, I showed that a network of causal principles constitutes a functional understanding of a system you are troubleshooting. I believe that understanding and constructing causal representations is the most powerful kind of problem analysis that learners may use.

The premise of this chapter is that the most essential cognitive skill required to solve problems is causal reasoning. Problems consist of problem factors or elements that are related causally. Uncovering those causal relationships embedded in problems is essential for learning how to solve them.

Figure 17.1 presents a graphic overview of this chapter. As illustrated in Figure 17.1 (upper left), the purposes for causal relationships are making predictions, implications, inferences, and explanations, all of which are necessary for problem solving. Later, I describe the covariational and mechanistic attributes of causal relationships (bottom). Finally, I describe various methods for helping learners articulate the causal relationships (upper right) that define any problem space.

WHAT ARE THE PURPOSES OF CAUSAL RELATIONSHIPS?

As the philosopher David Hume claimed, causal reasoning is the "cement of the universe" (Hume 1938, p. x). As intellectual cement, causality binds together reasoning processes that are common to all disciplines, including making predictions, drawing implications, making inferences, and articulating explanations (see Figure 17.1).

What Are Predictions?

Reasoning from a condition or set of conditions or states of an event to the possible effect(s) that may result from those states is called *prediction*. Predictions are probabilistic relationships between causal antecedent(s) and effect(s), because a potentially large number of causal relationships may participate in the occurrence of the effect (described later as causal conjunction). The two primary functions of predictions are forecasting an event (e.g., economic or meteorological forecasting) and testing of hypotheses to confirm or refute scientific assumptions. Predictions support experimentation; they are the hypotheses of experiments. A sociologist, for example, predicts (hypothesizes) that changes in economic well-being may result in changes in social status. Scientific predictions (hypotheses) are empirically tested for their validity. A psychologist may predict that changes in

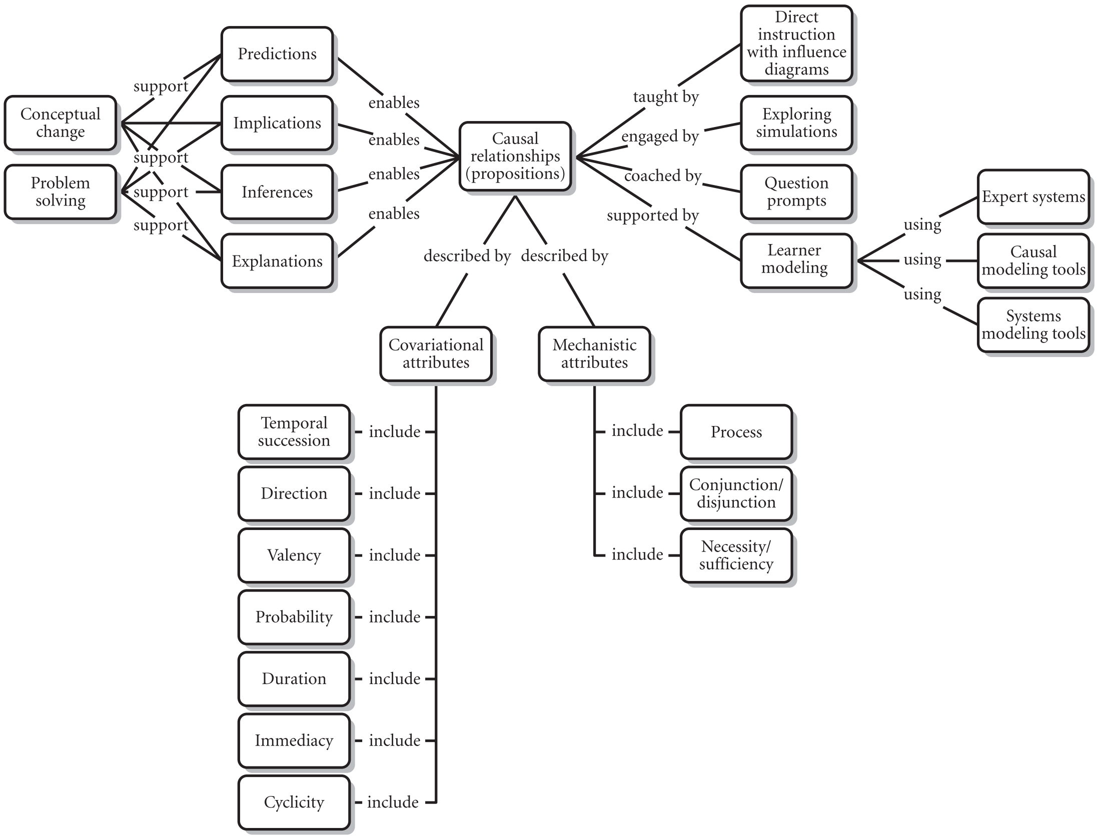


Figure 17.1 Graphic organizer of Chapter 17.

environmental conditions, stress for example, will affect a person's behavior. Predictions assume a deterministic relationship between cause and effect, that is, that forces in the cause reliably determine an effect. Aristotle believed that everything is determined in accordance with causal rules (teleological form of causal reasoning). However, in everyday life, causality is less predictable.

What Are Implications?

Another less deterministic form of prediction is to draw implications from a set of conditions or states based upon plausible cause–effect relationships. To imply is to entail or entangle events or to involve an effect as a consequence of some cause without necessarily knowing what the effect will be. Drawing implications involves identifying anticipated or unanticipated consequences from a causal antecedent. For example, the implications of any new law passed by Congress are potentially complex. The intended outcome of the law is often supplanted by other unintended political, social, or economic outcomes. Therefore, implications of any event cannot be predicted with any degree of certitude. As such, implications represent a conditional form of prediction that is less deterministic (teleological) than a hypothesis. Implications have received very little research or analysis in psychology or philosophy, so little is known about implicational reasoning.

What Are Inferences?

When an outcome or state exists for which the causal agent is unknown, then an inference is required. That is, reasoning backwards from effect to cause requires the process of inference. A primary function of inferences is diagnosis. Diagnostic causal reasoning is predominantly deterministic because only a determinable number of causes can be inferred to produce the effect. That is, the effect is already known with a fair amount of certainty, and therefore only a limited number of causes can be inferred for the specific conditions in which it occurred. Diagnosis is the identification of a cause, an origin, or a reason for something that has occurred. In medicine, diagnosis seeks to identify the cause or origin of a disease or disorder. For example, based on symptoms, historical factors, and test results of patients that are thought to be abnormal, a physician attempts to infer the cause(s) of that illness state. Medical specialties are based in part on an understanding of different subsystems in the human body and the cause–effect relationships that determine various states. In medicine, some relationships among symptoms are not causal. Those correlations without causal mechanisms are called syndromes. It's possible to treat syndromes palliatively, but you can't cure them. Likewise, automobile mechanics specialize in certain makes of cars because of an increased awareness of the continuously increasing complexity of causal (functional) connections in different makes of automobiles.

Prediction and inference represent the two most common types of causal reasoning. In order to understand the relationship between predictions, actions, and outcomes, one needs a causal model, developed through backward inference (diagnosis). Predictions involve forward inference. Forward inference (predictions) depends on backward reasoning (Einhorn & Hogarth, 1982). They cite Kierkegaard who claimed that "Life can only be understood backwards; but it must be lived forward."

Do these types of causality call on different processes? A few researchers have compared the processing required for predictions vs. inferences. Because causal schemas evolve from causes to consequences, it is easier to reason from causes to consequences (prediction) than consequences to causes (inference, diagnosis) (Tversky & Kahneman, 1980). In their study, participants judged predictions to be easier than inferences (diagnosis). The implication is that problems that call on predictions will be easier to solve than problems calling on inferences.

WHY REASON CAUSALLY?

Understanding causal relationships among the concepts in any discipline or system is essential for explaining how things work. If a problem solver does not understand how things work in any discipline or system, then it will be nearly impossible to solve original problems in that discipline or system. For example, troubleshooters must understand the causal relationships in the system in order to locate fault states. Even flying a plane requires the pilot to have a causal model of how the plane flies.

The depth of understanding of the causal or functional model of the system depends on the problem being solved. For example, an airframe mechanic needs a much more detailed causal model (and a different one) than the pilot, of the same plane. The engineer who designed the plane has a different causal map than the mechanic or the pilot.

How Do Causal Relationships Facilitate Explanation?

Causality is endemic to understanding virtually every discipline. Causality is essential for understanding all forms of scientific reasoning (Klahr, 2000; Kuhn, 2002; Kuhn & Dean, 2004; Zimmerman, 2000). Scientific explanations make very heavy use of what Aristotle called formal and efficient causes, which describe the forces that made those things. Reasoning in the social sciences and humanities requires understanding human goals, intentions, motives or purposes that are subject to formal (teleological) causes that describe the goals or intentions of causal agents and the effects on human behavior.

Explaining any entity requires more than an awareness of the parts of that entity. Explanations require functional knowledge of the entity or system being explained. Functional knowledge includes the comprehension of the function and structure of the interrelationships among the components in any system and the causal relationships between them (Sembugamoorthy & Chandrasekaran, 1986). You cannot fully explain any entity or event without understanding it causally. For example, the process of diagnosing disease states requires that physicians' explanations of diseases include causal networks that depict the combination of inferences needed to reach a diagnosis (Thagard, 2000b). Explanation of phenomena cannot occur without the abilities to predict, implicate, and infer.

How Do Causal Relationships Facilitate Problem Solving?

Robust conceptual models of any discipline are essential for learning to solve problems. Problem solving is the most ubiquitous cognitive activity in everyday and professional contexts (Jonassen, 2004). Although expert problem solvers index their knowledge by experiences (Jonassen & Hung, 2006), novices and advanced beginners must develop conceptual models of the causal relationships that comprise the problem space for virtually any kind of problem. For example, medical reasoning involves a causal process for making diagnostic or therapeutic decisions or understanding the pathology of a disease process (Patel, Arocha, & Zhang, 2005). In troubleshooting problems, causal reasoning about the system is necessary for predicting normal system behavior, integrating observations into actual system behavior, finding discrepancies between them, or finding discrepancies between observed behavior and hypothetical behavior (Yoon & Hammer, 1988). Amsel, Langer, and Loutzenhiser (1991) found that causal reasoning was essential for all forms of problem solving; however, lawyers' organization of causal inference rules is different than psychologists' and novice adults'. In Chapter 3, I cite research that shows that trial lawyers rely on causal stories in order to make their cases. Different kinds of problems in different disciplines focus on different causal relationships (predictions, inferences, implications, and explanations).

WHAT ARE THE ATTRIBUTES OF CAUSAL PROPOSITIONS?

In this next section, I describe the nature of causal relationships and the attributes of causal relationships that enable the predictions, implications, inferences, and explanations (see Figure 17.1). These attributes describe covariational (quantitative) and mechanistic (qualitative) attributes of causal relationships. We set the stage by providing background descriptions of causal relationships and of covariational and mechanistic views.

Causality is the relationship that is ascribed between two or more entities where one incident, action, or the presence of certain conditions determines the occurrence or nonoccurrence of another entity, action, or condition. Hume was one of the first modern philosophers to explore causality. He identified the important attributes of causation:

> 1. The cause and effect must be contiguous in space and time.
> 2. The cause must be prior to the effect.
> 3. There must be a constant union betwixt the cause and effect.
>
> (Hume, 2000, p. 116)

Although causal relationships are usually induced empirically based on observations, empirical descriptions are insufficient for understanding the causal relationship. Contemporary accounts of causality emphasize three main principles that validate a causal relationship, including covariation (co-occurrence) principle, priority principle, and mechanism principle (Bullock, Gelman, & Baillargeon, 1982). Covariation is the degree or extent to which one element consistently affects another as described by Hume, which describes the empirical relationships between cause and effect. Covariation is expressed quantitatively in terms of probabilities and strength of relationship. The mechanism principle describes causal relationships qualitatively, in terms of the conceptual mechanisms that describe why a cause results in an effect. Why does the cause result in the effect?

The covariational and the mechanism principles are the two most common conceptual frameworks for studying causal reasoning (Ahn, Kalish, Medin, & Gelman, 1995; Thagard, 2000a). Instead of being separate descriptions of causal relationships, covariational and mechanistic explanations are reciprocal. Both are necessary for understanding causal relationships; neither is sufficient. Although learners can induce a covarying relationship between two variables based on observations (as often happens in simulations—see Chapter 14), failure to construct an understanding of the explanatory mechanism that shows how and why the covariation occurs means the relationship will not be understood (Hedstrom & Swedberg, 1998; Mahoney, 2001).

In order to construct covariational and mechanistic explanations, several dimensions of covariation and mechanism are required. In order to be able to reason causally to make inferences and predictions in order to solve problems, learners must be able to explain the multiple facets of causal relationships, including covariational and mechanistic attributes of any causal proposition. These attributes are illustrated in Figure 17.1. In order to manifest deep-level learning, students must learn how to explain and apply each of the covariational and mechanistic attributes shown in Figure 17.1 for any of the causal relationships they are studying. Being able to apply those attributes in order to make predictions, implications, and inferences is essential to learning to solve problems. I describe these attributes next.

What Are Covariational Attributes of Causal Relationships?

Causes are usually inferred from observational data (Steyvers, Tenenbaum, Wagenmakers, & Blum, 2003). Repeated occurrences of the association between the cause and effect are necessary conditions for a causal relationship to be legitimate. When conditions covary consistently, we infer a causal relationship.

In order to be able to explain and apply causal relationships, learners must be able explain the following covariational attributes for any causal relationships they are studying. As designers, we must design, develop, and implement tools for supporting those explanations.

What Is Temporal Succession in Causal Relationships?

According to the principle of temporal succession (temporal priority), a cause C must be present for an effect E to occur, that is, causes precede effects. In order to understand and apply causal relationships, learners must be able to describe the temporal sequence of any causal relationship. For each cause that results in an effect, even if those causes are conjunctive (multiple, interacting causes), learners must be able to accurately describe the order of that relationship. Learners must be able to distinguish a concept as cause or effect, depending on its temporal position in the relationship.

Temporal succession alone is insufficient to establish causality because it does not necessarily imply a causal relationship. Many phenomena are temporally contiguous (they covary) but do not necessarily imply causality (Fugelsang & Thompson, 2003). For example, Monday always precedes Tuesday, but no causality exists. So it is necessary to confirm the causal relationship based on the direction, probability, and valency (described next) of the cause–effect link.

What Is Direction in Causal Relationships?

In order to understand and apply causal relationships, learners must also be able to describe the direction of any causal relationship. The direction of a causal relationship describes the direction of the effect that results from the cause. Does the cause have a positive or negative effect? The directionality of cause–effect relationships should be described as "an increase in cause C results in an increase (decrease) of effect E" or "a decrease in cause C results in an increase (decrease) in effect E." It is essential that learners be able to explain whether a causal relationship is positive or negative.

What Is the Valency (Strength) of Causal Relationships?

Covariation is also described by the strength of the relationship between cause and effect. In addition to the direction of the effect (positive or negative), how large is the effect, based on their shared variance (Kelley, 1973). Understanding covariation requires an understanding the extent of the effect that results from the cause. An increase/decrease in the cause C will have a slight/small/moderate/or great increase/decrease on effect E. Valency describes the strength or amount of effect of the causal relationship. The strength of that relationship may be expressed semantically (as above) or quantitative in terms of actual amounts, percentage increase/decrease or changes in variance expressed in regression equations or structural equation modeling, the most common quantitative representations of valency. In order to understand and apply causal relationships, learners must also be able to describe the valency of any causal relationship.

What Is the Probability of Causal Relationships?

Covariation usually represents the probability of the cause producing the effect, a quantitative representation of causal reasoning (Thagard, 2000a). Therefore, the covariation index is most often expressed as the difference between the conditional probability of the target effect E, given the presence of the conditional factor C and the probability, given the absence of the factor ($p(E|C)$—$p(E|{\sim}C)$ (Cheng & Novick, 1992; Waldman & Hagmeyer, 1995). Also referred to as the regularity or consistency view, covariation is often expressed as a probabilistic or contingency model (Cheng & Novick, 1992) that considers the probability of an effect minus the probability of an effect occurring when cause is absent.

In order to understand and apply causal relationships, learners must also be able to describe the probability of the occurrence of any causal relationship. Relationships are classified as causal based on the probability that they are produced by those mechanisms (Rehder, 2003). Rehder found that participants rated cause–effect pairs based on correlations between feature pairs that are directly connected by causal relationships. Probability may also be thought of as the degree of belief that any person believes that relationship exists.

What Is Duration of Causal Relationships?

In order to understand and apply causal relationships, learners must also be able to describe the duration of any causal relationship. How long does the effect persist? Is it short-term, long-term, or constant? Different temporal units of analysis are necessary to describe the duration (nano-seconds to years). The duration of any causal relationship needs to be described by learners who are trying to solve problems or explain phenomena.

What Is the Immediacy/Delay in Causal Relationships?

How readily does cause produce the effect? Another covariational indicator of causality includes the assumptions about temporal delays between causes and effects. Most people assume that effects of causes are immediate. However, effects may be delayed by numerous factors. When you alter the temperature control valve in a shower, the effect on water temperature is usually delayed by a small amount. In macroeconomic systems, those delays can be considerable. Delays are important because different temporal assumptions about causal delays may lead to dramatically different causal judgments. Learners' prior assumptions about temporal lags guide their selection and interpretation of probable causes and so must also be described by learners.

What Is Cyclical Causality?

So far in this chapter, I have treated causality as a unidirectional process. Antecedent causes result in changes in some effects. But Newton's third law states that, "For every action, there is an equal and opposite reaction." Systems-dynamics theory regards causality as cyclical. Systems are dynamic when their components are related to changes in other system components, that is, components of a system affect other components which, in turn, affect the original or other components. Systems dynamicists do not assume that, for instance, hunger causes eating. Rather, hunger causes eating then feeds back to influence the level of hunger. Feedback is the means by which causal relations are controlled.

The influences of system components on each other can be positive or negative. Positive influences are those in which a directional change in one component causes a similar change in another. The relationships are cyclical. Eating influences the habit of eating, which influences hunger, which influences eating. However, dynamic changes result from the interplay of multiple factors, both positive and negative. Positive influences are reinforcing; negative influences are regulatory. Eating influences fullness, which negatively influences (or regulates) hunger. A system in which positive factors and negative factors increase or decrease a factor equally is in balance. For instance, eating habit and fullness counterbalance each other. If these forces are equal, there will be no change in eating and therefore weight. When one force exerts a greater influence, eating and weight will rise or fall. In order to understand and apply causal relationships, learners must also be able to identify any cyclical relationships among causal relationships.

What Are Mechanistic Attributes of Causal Relationships?

In addition to observing covariation among causes and effects, qualitative understanding of relationships is necessary for understanding causal relationships. Many contemporary causal theorists argue that empirical inductions, while necessary, are insufficient for understanding causal relationships. "Patterns of association and covariation are interpreted in light of beliefs about mechanisms and causal powers that are fundamental elements of conceptions of causal relations" (Ahn & Kalish, 2000, p. 205). Mechanisms are conceptual descriptions of causal relationship. They specify the way that something works, answering "why" questions in order to specify "how" the event occurred. How does oxygen feed a fire? Causal-mechanism explanations attempt to fit the empirical findings into a causal structure in order to explain an event (Salmon, 1984).

Understanding causal mechanisms refers to people's beliefs about the transmission of influence from cause to effect, also known as causal power. This attribute is required to distinguish causality from correlation. In covariational relationships, things covary (they are conjoined). However, in causal relationships, there is a genetic relationship between cause and effect (Bunge, 1979), a kind of conceptual force or causal power that is transmitted from the cause to the effect (Ahn & Kalish, 2000; Cheng, 1997). For example, greed exerts or transmits a causal power that results in corruption, or so we believe. "To describe the cause or causes of an event is to explain why it occurred" (Kuhn, 1977, p. 23). Mechanisms represent qualitative understanding because they explain how and why the cause(s) produces the effect (Thagard, 2000a).

In order to understand and use causal relationships to make predictions, inferences, or explanations, learners must be able to describe different mechanistic attributes of causal relationships. I describe these next.

What Is Causal Process in Causal Relationships?

Causation is most commonly conceived on a general level. For example, most of us attribute the contraction of a common cold to someone sneezing near us. While the sneeze may be the key causal agent, the process of viral transmission is much more complex than that. So, students of medicine, microbiology, or other related fields must be able to explain the numerous causal relationships necessary to transmit germs and cause a cold. Germs are dispersed through the air by the sneeze, some of which attach to host cells. The virus injects its genetic material into the host cell. That genetic code is copied into the host cell, breaking out of it and invading other cells, all of which sets off complex immunological reactions, including the distribution of mast cells to the site of the infection, the release of histamines causing inflammation of the tissue causing more immune cells to be delivered to fight off the infection. If learners cannot adequately articulate these complex causal processes, their conceptual understanding is overly simplified.

What Is Conjunction/Disjunction Process in Causal Relationships?

Oversimplified understanding of causality also fails to recognize the roles of conjunctive or disjunctive causes. Most causal relationships result from a conjunction of different types of causes. Conjunction occurs when two or more causes must be jointly present in order to produce the effect. For example, many people believe that terrorism results from overzealous adherence to religious dogma. However, effects are almost invariably produced by multiple factors that are individually necessary and jointly sufficient to produce the effect (Cheng, 1997). As indicated before, causal reasoning is too often conceived at a general level that must be explicated by identifying the conjunction or disjunction of causes that are necessary to produce the effect (Marini & Singer, 1988). Terrorism is caused by the conjunction of religious beliefs, poverty, repression, aggressive societal tendencies, and a host of other potential causes.

When causes conjoin, it is important to isolate their contributions to the effect. Causes are most often thought to be direct, where a cause (heat) has a direct effect (pressure). However, not all causes have a direct effect. Rather, many causes are enabling rather than influencing.

Learners must be able to distinguish between influencing and enabling causes. For example, a lightning strike or dropped cigarette may be the direct cause of a forest fire, but the fire could not have occurred without enabling conditions such as the presence of contiguous dry, combustible material and oxygen. The lightning or cigarette must be conjoined with other enabling conditions in order to produce the fire. These factors are combined in non-independent ways to produce the effect (Cheng, 1997).

Disjunctions identify a combination of causes, any one of which may produce the effect, but do not pinpoint the actual cause that produced the effect in this case (Marini & Singer, 1988). Identifying the cause of death for someone who is in very poor health may be impossible or irrelevant, given the plurality of factors that could have been the cause. A disjunction of causes occurs when the effect may be produced by each of several factors alone, and joint occurrence of two or more do not alter the effect. In order to understand and apply causal relationships, learners must also be able to describe the conjunctive and disjunctive relationships among more general cause–effect relationships.

What Is Necessity/Sufficiency in Causal Relationships?

In order to understand the role of different conjunctive causes, it is important that learners also be able to describe all causes as necessary or sufficient. In the previous section, I said that causes may have an influencing or enabling effect. Influencing effects in mechanistic explanations of causality must also include indications about its necessity and sufficiency. Causal relationships are represented as necessary or sufficient conditions for an effect to occur. Necessity/sufficiency is a difficult but essential attribute of causality. Necessity is a more complex concept than sufficiency. For sufficiency, people only verify whether the cause is always followed by the effect, whereas for necessity, there are two possibilities that can be verified: does the cause always precede the effect, and can the effect occur without the cause. More importantly, both concepts have a different structure: necessity is considered as an all-or-none property whereas sufficiency is a more liberal characteristic (Verschueren, Schroyens, & d'Ydewalle, 2004).

How Can We Resolve Covariational and Mechanistic Explanations?

There are two interdependent forms of reasoning required to induce and explain causal relationships: covariational and mechanistic. Despite their fundamental conceptual differences, covariations and mechanisms are complementary (Ahn et al., 1995; Ahn & Kalish, 2000; Bunge, 2004; Glennan, 2002). Understanding causality depends on both kinds of representations. It is impossible to make sense of empirical information without applying some conceptual framework to interpret that information (Waldman & Holyoak, 1992; Waldman, Holyoak, & Fratiannne, 1995).

HOW CAN WE FACILITATE CAUSAL REASONING?

In order to solve problems, learners must understand the causal relationships that describe the problems covariationally in terms of direction, probability, valency, duration, and responsiveness and mechanistically in terms of causal explication, conjunctions/disjunctions, and necessity/sufficiency. In this section, I describe methods for supporting the learning of those causal attributes. There are three classes of methods that may be used to enhance causal learning:

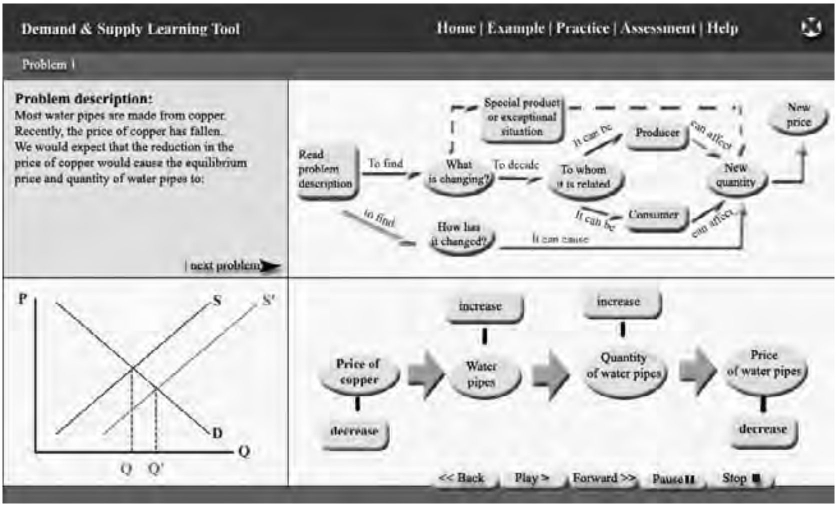
1. influence that conveys causal relationships;
2. exploring causal relationships in simulations;
3. learner modeling of causal relationships (see Figure 17.1).

No direct comparisons of these methods have been made.

How Can We Convey Causal Relationships Through Influence Diagrams?

One method for conveying information about causal relationships is through the use of influence diagrams. Influence diagrams are visual displays that depict causal relationships among the variables in complex phenomena and explicate the underlying mechanisms that govern the relations (Howard & Matheson, 1989). Influence diagrams are especially useful for representing causal reasoning processes because they offer a set of comprehensive directional (causal) relation indicators that enable learners to represent a problem space causally and conceptually (Newell & Simon, 1972). Influence diagrams visualize the causal structure of the phenomena (Shapiro, van den Broek, & Fletcher, 1995). Figure 17.2 illustrates an interactive influence diagram for explaining the causal relationships in supply and demand problems. Hung and Jonassen (2006) found that students who studied mechanistic models of causality in the form of influence diagrams while learning to solve physics problems performed better on a test of conceptual physics than students who experimented with simulations (described next).

Influence diagrams (see Figure 17.2) diagrammatically represent temporal succession and direction but do not normally convey covariational attributes of valency, probability, duration, or immediacy. In



Problem description:
Most water pipes are made from copper.
Recently, the price of copper has fallen.
We would expect that the reduction in the price of copper would cause the equilibrium price and quantity of water pipes to:

Figure 17.2 Influence diagram illustrating causal relationships in economics.

order to explicate those attributes, verbal explanations or visual codes added to the diagram would be necessary. It is probable that the visual codes would add cognitive load to the interpretation of the diagram. Influence diagrams are especially effective for representing mechanistic attributes, including processes and conjunctions and disjunctions. Necessity and sufficiency would require verbal elaborations or visual codes added to the diagram. Cyclicity is easily conveyed in the form of causal loop diagrams (see Figure 17.3), another form of influence diagrams that are associated with systems dynamics. That diagram shows that eating is positively influenced by hunger. Eating positively affects the habit of eating as well as weight; however, eating influences fullness, which negatively influences hunger which in turn controls eating. Both forms of influence diagrams can be used to explain difference causal phenomena.

How Can Students Explore Causality?

Students may also explore causal relationships through the use of simulations (see Chapter 14). Simulations are environments where students can manipulate values for components of a system in order to test the covariational effects of one or more variables on others. With simulations, "the main task of the learner is to infer, through experimentation, characteristics of the model underlying the simulation" (de Jong & van Joolingen, 1998, p. 179). When learners interact with the simulation, change values of (input) variables and observe the results on the values

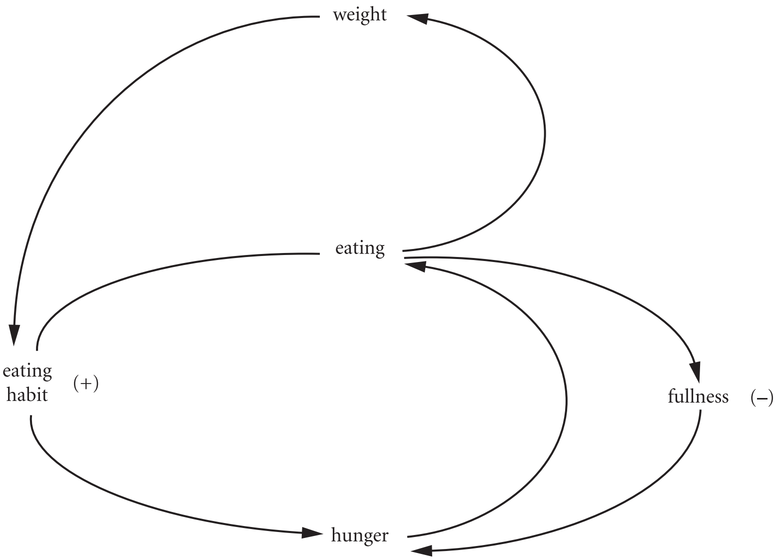


Figure 17.3 Causal loop diagram of the hunger cycle.

of other (output) variables, they are testing the covariational effects of factors. That is, they are exploring the extent of effects of causal agents on other factors. Because of the limitations on learner interaction with the model, simulations can support learning only covariational attributes of direction, valency, and probability. It is difficult to convey duration and responsiveness in the simulation model, and mechanistic attributes are rarely conveyed in any coherent way in simulations. Therefore, when using simulations to learn about causal relationships, it is important that students reflect on their observations and explain the mechanisms that underlie each of the causal relationships that they have identified. For example, in the diagram in Figure 17.2, why does a decrease in the price of copper positively affect the supply of copper pipes?

How Can We Prompt with Questions?

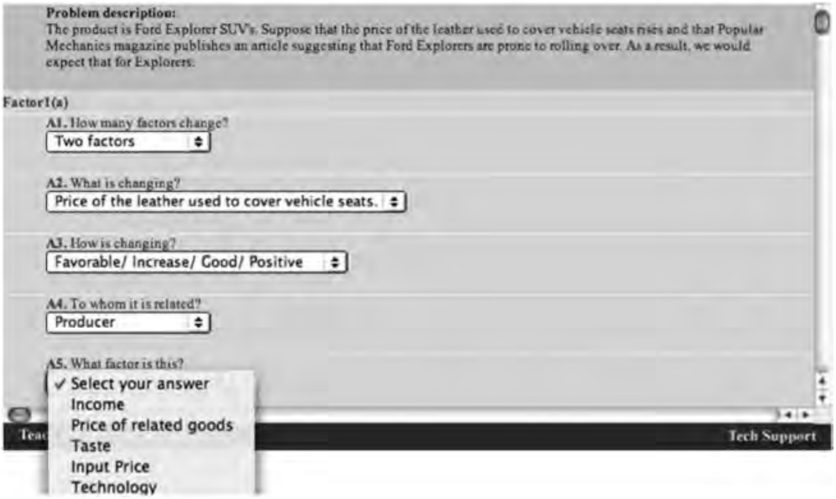
As explained in Chapter 18, questioning is one of the most fundamental cognitive components that guide human reasoning (Graesser, Baggett, & Williams, 1996). Answering deep-reasoning questions helps students to articulate causal processes (Graesser, Baggett, et al., 1996). When students engage in question-driven explanatory reasoning, their learning and problem solving improves (Graesser, Baggett, et al., 1996). In order to support problem solving, you should question learners about causal relationships that underlie the problem they are solving.

Learners select answers to causally oriented questions from a menu of questions. For example, in the environment illustrated in Figure 17.4, students are queried about causal relationships that underlie supply-and-demand problems in order to help the understand the causal process that drive that kind of problem.

Questioning, such as that in Figure 17.4, works by focusing the learner's attention to covariational and mechanistic attributes of each of the relationships in the problem. Questions may be used to focus attention on any covariational attributes, including direction, valency, probability, duration, responsiveness as well as mechanistic attributes of process, conjunctions/disjunctions, and necessity/sufficiency. Being able to effectively answer those questions require prerequisite understanding of how each of those attributes relate to any causal relationship, making this a more difficult way to support learning.

How Can Students Model Causal Relationships

Rather than using direct instruction to convey the meaning of causal relationships or questions to coach understanding, a number of modeling tools and environments may be used by students to construct models of problems. See Chapter 19 for a description of several of these modeling tools and how they work. The model that students construct using those tools convey their understanding of important causal relationships and predict how well students will be able to solve problems.



Problem description:
The product is Ford Explorer SUV's. Suppose that the price of the leather used to cover vehicle seats rises and that Popular Mechanics magazine publishes an article suggesting that Ford Explorers are prone to rolling over. As a result, we would expect that for Explorers:

Factor1(a)

A1. How many factors change?
Two factors

A2. What is changing?
Price of the leather used to cover vehicle seats.

A3. How is changing?
Favorable/ Increase/ Good/ Positive

A4. To whom it is related?
Producer

A5. What factor is this?

Figure 17.4 Questioning about causal relationships.

HOW CAN CAUSAL MODELING BE USED AS TASK ANALYSIS?

Although described last in this chapter, perhaps the most important purpose for causal mapping is as a form of task analysis when designing problem-solving learning environments (PSLEs). Task analysis is a process performed by instructional designers to articulate the nature of the learning task. In this chapter, I have argued that the cognitive basis of problem solving is causality. So, in my classes on problem solving where students design PSLEs, I first teach the learners to construct causal maps of the problems that students will be expected to learn in order to analyze the nature of the problem for which they are designing the PSLE.

18

QUESTION STRATEGIES FOR SUPPORTING PROBLEM SOLVING

WHY ASK QUESTIONS?

Questioning is one of the most fundamental cognitive components that guide human reasoning (Graesser, Baggett, & Williams, 1996). "It could be argued that questions are at the heart of virtually any complex task that an adult performs" (Graesser & Olde, 2003, p. 524), especially problem solving. Problems are situations for which an answer or solution is unknown, that is, a question to be answered in some context (Jonassen, 2007). Given that all problems include unknowns, it should be obvious that asking and answering questions are essential to problem solving. In order to solve problems, it is important that learners acquire the skills and strategies of question asking as well as question answering. What do I know about the situation? Is that a normal state? Where is the likely fault? What is causing that fault? How can I correct that fault? Questions are asked when people experience cognitive disequilibrium while solving problems, which is triggered by contradictions, anomalies, obstacles, salient contrasts, and uncertainty (Graesser & Olde, 2003). They presented learners with troubleshooting tasks and found that those who comprehended the device better asked no more questions than those with shallow comprehension; however, they generated higher-quality questions in order to produce better explanations of the device they were troubleshooting. That is, the quality of question asked is a stronger indicator of comprehension, not the quantity. The best questions were explanation-based such as:

- why did X occur;
- how did X occur;
- what are the consequences of X;
- what if X occurs;
- what if X does not occur.

Question-driven explanatory reasoning predicts that learning improves to the extent that learners generate and answer questions requiring explanatory reasoning (Graesser, Baggett, et al., 1996).

Questioning aids problem solving in many ways. Answering deep-reasoning questions articulates causal processes (see Chapter 17) as well as goals, plans, actions, and logical justification (Graesser, Baggett, et al., 1996), all of which are shown in other chapters in this book to be essential processes for solving problems. During problem solving, questions are essential for guiding student reasoning as they work to comprehend the problem and to generate solutions. What kind of problem is this? Have I solved a problem like this before? Does my solution make sense? The question–answer rhetorical structure is the most common dialogue pattern in naturalistic conversation (Graesser, Swamer, Baggett, & Sell, 1996). Question-driven explanatory reasoning predicts that learning improves to the extent that learners generate and answer questions requiring explanatory reasoning (Graesser, Swamer, et al., 1996). Questioning has long been acknowledged as an effective comprehension-fostering cognitive strategy (Palinscar & Brown, 1984). Questions arise in reciprocal relationship to decisions that must be made while solving problems. Learning to solve problems is aided by asking questions to guide student analysis. Transfer of the skill of questioning occurs when students are able to generate explanatory questions on their own when presented with new problems.

When learning to solve problems, questions may function as powerful scaffolds. Although there exist numerous conceptions of scaffolding in the literature, I argue that scaffolding represents some manipulation of the task itself by the teacher or the instructional system. That may include performing part of the task for the student, thereby supplanting the student's ability to perform that part of the task; providing cognitive tools that helps the learner perform the task; or adjusting the nature or difficulty of the task. A learner's request for scaffolding might take the form of a "Help Me Do This" button. Solving virtually any problem requires that learners ask questions in order to assess what they know about the problem, what they need to know, and what they need to do in order to solve it. In this chapter, I describe how questions can be inserted into problem-solving learning environments (PSLEs).

Like all good scaffolds, after completing some number of problems, those questions should be faded out, requiring the learner to generate those questions themselves. The goal of questioning as a cognitive strategy is to enable learners to generate deep-level questions that enhance problem solving. After describing the kinds of questions that can be asked of students and the kinds of questions that students should learn to ask themselves while learning to solve problems, I describe how those different kinds of questions can be used by teachers or embedded in instructional systems.

WHAT KINDS OF QUESTIONS ARE THERE?

The nature of the thinking that is elicited by questions depends on the frequency and the nature of the questions that are asked. Despite the importance of question asking by students to conceptual understanding, students very seldom ask questions in classrooms (Graesser & Person, 1994). There is usually little opportunity to ask questions in most classrooms. However, in individual tutoring sessions, students ask 240 times as many questions as they do in classrooms (Graesser & Person, 1994). That is why individual tutoring is so much more effective than large-group, classroom instruction. Graesser and Person also found that students' achievement was related to the quality of questions asked but not the frequency. A question reflects the level of thought required to answer it (Dori & Herscovitz, 1999), so asking good questions is more effective than asking a lot of questions. In this section, I will briefly describe and exemplify different kinds of quality questions.

Graesser et al. conducted a number of studies in an effort to develop taxonomies of question types. For example, Graesser, Person, and Huber (1992) identified several kinds of questions, including:

- **Verification**: Is the answer 5? Are droplets drops?
- **Concept completion**: Who is that? In which liquids does nitrogen dissolve?
- **Disjunctive**: Is a or b the answer? Are clouds made of water vapor or are they made of droplets?
- **Definition**: What is a t test? What is solubility?
- **Example**: What is an example of pollution?
- **Comparison**: What is the difference between water vapor and water droplets?
- **Interpretation**: What is happening? Does that graph show a main effect for A?
- **Causal antecedent**: Why didn't the car start? Why does it rain sometimes more often than others?

- **Causal consequence**: What happens when it gets too hot? If there is no water vapor in air, what happens?
- **Goal orientation**: Why did you drive to St. Louis? What was the purpose of the City's cutting taxes?
- **Instrumental procedural**: How do you do that? How is a storm created?
- **Enablement**: What do you use to distill water into vapor?
- **Expectational**: Why didn't it arrive?
- **Judgmental**: How accurate is that? What do you think about the new taxes?
- **Assertion**: I don't understand.
- **Request/directive**: Would you turn on the light? How do I get a printout of this?
- **Quantification**: What is the average speed of a drop of water?
- **Feature specification**: What kind of polluting process is present?
- **Procedural/process**: How do you do factor this equation?
- **Conversation**: What did she say?
- **Relational**: How much larger is an atom than a molecule?
- **Gist**: What is the main idea of the passage?
- **Implication**: What could happen if taxes were increased?
- **Inference**: Why did the recession occur? What caused it?
- **Prediction**: What will happen if theses two liquids are combined?

Each of these kinds of questions, in the appropriate context, will enhance students' understanding of material they are studying. Those questions may be used to organize a lesson, to guide students' study habits, to invoke metacognitive reasoning (see Chapter 21), or to serve a multitude of purposes.

Questioning is often ineffective because students mimic the expectations that are set by the teacher. Because their examinations require recall performance, students too often ask definition questions, anticipating the need to know the answer for the examination. However, there are so many other kinds of questions that are required for deeper-level comprehension of ideas. It is generally accepted that questions that reflect deeper comprehension begin with why, why not, how, what if, or what if not. As we shall see, certain kinds of questions such as interpretation, comparison, prediction, causal antecedents and consequents, inference, and instrumental/procedural are more important to learning to solve problems than other kinds of questions.

Effective questioning can provide new interpretations of disciplines. That is, they can get learners to consider disciplinary ideas in very different ways. For example, in their book, *The Art of Problem Posing*, Brown and Walter (1983) suggest posing questions such as the following rather than asking math and science students to only solve formulas and calculate answers:

- What purpose does the formula serve?
- What is the number of objects or cases satisfying this condition?
- What is the range of the answer?
- What is the pattern in this case?
- Is there a counterexample?
- Is there a solution?
- Can we find it?
- Can we prove it?
- When is it false? When true?
- Is there a limiting case?
- Is there a uniting theme?
- What does it remind you of?
- What do I need in order to prove it?
- What are the key features of the situation?
- What are the key constraints?

These questions elicit qualitative understanding of quantitative problems. As I have discussed in different chapters, qualitative or conceptual understanding of problems is just as important, if not more so, than quantitative understanding of problems. If students do not understand the components and their interrelationships in a problem semantically, they will be unable to transfer any skills they develop. Because students are unaware of their conceptual limitations and because they have developed strategies for performing in expected ways, questions such as those suggested by Brown and Walter are likely to be unpopular with students initially. They need to develop new study scripts for thinking about what they are studying in ways that are able to answer such questions.

WHAT KINDS OF QUESTIONS SUPPORT PROBLEM SOLVING?

There exist different kinds of questions that will support problem solving in different ways. These different kinds of supporting questions are described next.

What Are Task-Relevant Problem-Solving Questions?

Perhaps the most obvious way to support problem solving is to ask questions or help learners to ask questions related to the problem-solving process. Questions have been shown to support ill-structured problem solving. For example, Ge and Land (2003, 2004) provided task-relevant question prompts that were related to the four major problem-solving processes:

1. problem representation;
2. solution generation;
3. justification;
4. monitoring and evaluation.

Questions included:

- How do I define the problem?
  - What are the parts of the problem?
  - What are the technical components?
  - What information do you need for this system? How will the system be used, by whom, and for what?
    - Who would be the users?
    - What information do you expect to be needed by the users?
    - What level of prior knowledge do you expect the users to have?
    - How would a user ideally interact with the proposed system?
- What solutions do I need to generate?
  - What should the system do?
    - How should the different technical components of the proposed system interrelate?
    - What are the risks?
  - What are my reasons or what is my argument for the proposed solutions?
    - How do I justify the specific system design?
    - Do I have evidence to support my solutions?
  - Am I on the right track?
    - Have I discussed the technical components and the issues with use?
    - Are there alternative solutions?
      - What are they?
      - How are they compared with my proposed system?
  - What argument can I make or what evidence do I have to convince the manager that my solution is the most viable?

Students who received question prompts produced better problem-solving reports on all four problem-solving processes, and they made more intentional effort to identify factors, information, and constraints during problem-solving phases. They organized and planned for and explicitly articulated their solutions, constructed arguments grounded in factors identified in the problem, intentionally evaluated their solutions, and justified the most viable solution. Questioning prompts help students to monitor and regulate the problem-solving process.

What Are Metacognitive Questions?

Metacognition (monitoring and regulating study strategies) has long been recognized as an important skill that is required to become a successful problem solver (see Chapter 21 for an expanded discussion of metacognitive skills). Successful learners monitor their own problem-solving processes. Schoenfeld (1985) recommended using metacognitive questioning to help learners monitor their problem-solving performance (e.g., What am I doing right now?). Various studies have shown that questions are effective for eliciting metacognition activities such as planning and reflection. Student's self-questioning is an important metacognitive activity (Rosenshine, Meister, & Chapman, 1996).

King (1991) provided strategic questions to guide cognitive and metacognitive activity while students used problem-solving software. The questions that she used focused on problem-solving process, including problem identification, search for solution, implementation and evaluation of the solution. Those questions included:

Planning questions

- What is the problem?
- What are we trying to do here?
- What do we know about the problem so far?
- What information is given to us?
- How can this help?
- What is our plan?
- Is there another way to do this?
- What would happen if . . . ?
- What should we do next?

Monitoring questions

- Are we using our plan or strategy?
- Do we need a new plan?
- Do we need a different strategy?
- Has our goal changed?
- What is our goal now?

- Are we on the right track?
- Are we getting closer to our goal?

Evaluating questions

- What worked?
- What didn't work?
- What would we do differently next time?

The students who were guided by questions while solving problems outperformed the unguided questioners and controls on actual problem-solving activities and also on a standardized problem-solving test. Although there is not a lot of research on metacognitive prompting in problem solving, studies to date show that training students in questioning facilitates the problem-solving process and outcomes.

Metacognitive prompts are even able to compensate for a lack of knowledge. Wineburg (2001) found that metacognitive knowledge can compensate for absence of relevant domain knowledge when metacognitive awareness leads to recognizing areas of limited understanding, adopting working hypotheses, asking questions, monitoring thinking, and revisiting early interpretations. When students self-regulate their learning by identifying their own knowledge deficits and then ask questions that remediate those deficits, they learn more effectively; however, those questioning skills generally require training (Graesser & Person, 1994). Many computer-based learning environments now use question prompts to guide students' metacognitive reasoning learning. Lin and Lehman (1999) found that justification prompts facilitated transfer to a contextually dissimilar problem while students were experimenting with online simulations. In a similar study, Hmelo and Day (1999) embedded questions in a medical simulation that focused students' attention on important clinical information. The importance of questioning and reflection while using simulations cannot be over-stressed.

What Questions Focus on Problem Schemas?

In order to be able to transfer problem-solving skills, especially for well-structured problems as in physics, it is important that learners construct meaningful problem schemas (see Chapter 15). Problem schemas consist of structural, procedural, and strategic models of the kind of problem being learned. That is, being able to classify the kind of problem being solved (Chi, Feltovich, & Glaser, 1981; Snyder, 2000). That is, in physics classes, students should be able to classify any mechanics problem as one of the following:

- kinematics;

- force;
- energy;
- momentum;
- rotation;
- oscillations.

In order to construct problem schemas that enable problem classification, they must construct structural, conceptual models of each problem type. Solving those problems requires construction and application of procedural and strategic models. Questions may be used to focus learners' attention on structural attributes of the problem. In our research, we have embedded questions into instruction that focus on attributes of the problem, such as:

- Which of the following are you provided with, either explicitly or implicitly, that would help you calculate the initial kinetic energy in the problem?
- Which of the following types of potential energies are relevant to this problem?
- What kinds of non-conservative forces do work in this problem?
- What information, directly provided, is needed to solve this problem?

These questions are not related to the calculation processes normally applied to physics problems. Rather, they focus attention on what components are in the problem and how those components are combined to constitute a conservation of energy problem.

When assessing the quality of problem schemas that have been constructed by students, there are different classes of questions that can focus on schema quality (see also Chapter 22). Text-editing questions identify whether problems contain sufficient, irrelevant, or missing information (Low & Over, 1989; Low, Over, Doolan, & Michell, 1994). For example, provide students with a problem that has a quantity that is missing, an extra quantity inserted into the problem, or just the right amount of information, such as:

> A 72-kilo motorcycle daredevil is attempting to jump across as many buses as possible. The takeoff ramp makes an angle of 18 degrees to the horizontal, and the landing ramp is identical to the takeoff ramp. The buses are parked side by side, and each bus is 3.5 meters wide. The cyclist leaves the ramp with a speed of 30 meters per second. What is the maximum number of buses over which the cyclist can jump?

Rather than asking students to compute the solution to the problem, ask them rather to specify whether the problem provides sufficient, missing, or irrelevant information for applying toward a solution. While this seems simple enough, it is extremely demanding for students because it focuses their understanding on the nature of the problem (problem schema) not the process for calculating a correct response.

Problem-classification questions present a problem and ask students to identify what kind of problem it is (e.g., conservation of energy, kinematics) (Chi et al., 1981). These questions require a coordinate set of readily identifiable problem classes, which generally limits this kind of question to well-structured problems.

Question sorts (aka card sorts) present a collection of problems and ask students to group the problems together based on how similar they are. Students typically generalize problem types based on surface-level similarities among problems (Chi et al., 1981; Dufresne, Gerace, Hardiman, & Mestre, 1992) rather than structural similarities between problems. Because of that disposition, it is easy to evaluate students' misconceptions about problems fairly easily.

What Questions Focus Analogical Reasoning?

An important strategy for helping students to better comprehend problem schemas is to require them to compare and contrast problem pairs in order to identify how they are structurally similar or dissimilar (see Chapters 11 and 17). The theory that best describes the required analogical reasoning is structure-mapping theory (Gentner, 1983), where mapping the analogue to the problem requires relating the structure of the example, experience, analogue, or alternative perspective to the structure of the problem independent of the surface objects in either. In order to do so, those surface features (which attract the attention of poor problem solvers) must be set aside. Then the structural relations must be compared on a one-to-one basis in the example and the problem.

There are several kinds of questions that can engage analogical comparison of problems. Problem-similarity questions present two problems and ask learners to identify on a scale how similar the problems are (Low & Over, 1989). Answers to such questions are normally evaluated by comparing student responses with expert responses.

Questions that focus student attention on the structural aspects of the problems may also be asked. In some of our research, we presented pairs of physics problems to students and asked questions such as:

> Which of the following quantities are directly given or known in Problem 1 and in Problem 2?
>
> 1. Initial position of the package.

2. Final position of the package.
3. Initial velocity of the package.
4. Final velocity of the package.

We asked similar questions about the acceleration or trajectories of objects in both problems. After answering the questions, we ask students to summarize the similarities and differences between the problems and to draw conclusions about the kinds of problem that they are. All of these questions focus on qualitative understanding of the nature of the problem. As stated before, if students do not construct a robust schema for each kind of problem they are learning to solve, then they will be unable to transfer that skill to other problems.

What Questions Focus Causal Reasoning?

In Chapter 17, I explicate the centrality of causal reasoning to problem solving. From a cognitive-processing perspective, problem solving is largely a process of understanding the causal relationships among the problem elements and making inferences about what caused a certain state or predicting what state will result from a set of conditions. That is, problem solutions are effects that result from causes. Asking questions about those causal relationships will focus students' attention on conceptual, qualitative understanding of the problem elements. For example, if students were attempting to diagnose possible problems associated with exercise, Osborne, Enduran, and Simon (2004) might recommend asking causally related questions such as:

> When you exercise, your skin gets redder especially in your face. Which state explains best the observation?
> - Your blood pressure increases, causing more blood to the surface of your skin.
> - Your blood is pumped to the surface for gaseous exchange to occur.
> - Your blood carries more oxygen and therefore is a deeper color.
> - Your blood gets closer to the surface for excess heat to be lost.

If students do not understand this cardiological principle, it is unlikely they will be able to solve related problems. During instruction, questions may also be posed to students that assess their understanding of concepts and principles being learned. For example, the following question used by Chi and Slotta (1993) calls for a prediction.

> A locomotive pulls a series of wagons. Which is the correct analysis of the situation?
> 1. The train moves forward because the locomotive pulls forward

slightly harder on the wagons than the wagons pull backward on the locomotive.

2. Because action always equals reaction, the locomotive cannot pull the wagon; the wagons pull backward just as hard as the locomotive pulls forward, so there is no motion.
3. The locomotive gets the wagons to move by giving them a tug during which the force on the wagons is momentarily greater than the force exerted by the wagons on the locomotive.
4. The locomotive's force on the wagons is as strong as the force of the wagons on the locomotive, but the frictional force on the locomotive is forward and large while the backward frictional force on the wagons is small.
5. The locomotive can pull the wagons forward only if it weighs more than the wagons.

This is a complex question that requires correctly identifying more than one causal force. If students are unable to correctly answer questions such as these, it is unlikely that they will be able to transfer the ability to solve this kind of problem. Posing causal relationship questions to students will enhance the understanding of domain principles and their ability to solve relevant domain problems.

What Are Argumentation Questions?

In Chapter 20, I describe the importance of argumentation to solving most kinds of problems, especially ill-structured problems. Because ill-structured problems seldom have known, definitive answers with uncertain solution criteria, it is important that students be able to argue for what they believe are the better solutions to the problems. Question prompts that elicit specific kinds of argumentative reasoning can help students to construct meaningful arguments. Kuhn (1991) provided specific questions to students based upon the skills of argument that she enumerated. For example:

- What do you think is the cause of school failure?
- How would you prove that this is the cause?
- What might somebody else, who does not agree with you, think is the cause of school failure?
- What could you tell her or him to show she or he is wrong?
- What might somebody else say to show that your opinion about the cause of school failure is wrong?
- What could you tell him or her to show he or she is wrong?

Depending upon the goal of the argument (controversy, compromise, or weighing), different questions can focus students' thinking about the issue. If you were facilitating a debate, then you might ask questions such as: "What solution might someone else recommend, and how would you respond to their reasons?" If you were seeking a compromise, then you might ask: "Is there a compromise or creative solution?" Carefully weighing arguments may be elicited by questions such as: "Which side is stronger and why?" Question prompts that scaffold students' abilities to generate their own questions to guide their analysis of any problem should be the goal of questioning.

Argumentation or justification questions can and should be used in combination with causal reasoning question. Before, I showed a question from Osborne et al. (2004) that seeks the cause of your skin getting redder. A follow-up question that seeks evidence in support of that causal relationship can make a powerful combination of comprehension questions.

1. Blood pressure in the capillaries is likely to be less as the volume has increased so that more blood can pass through them.
2. Gaseous exchange is when carbon dioxide diffuses out of the blood and oxygen enters the blood. This takes place in the lungs.
3. The more oxygen carried by the red blood cells deepens the color. This would be difficult to see. However, a quick test for anemia is to stretch your hand and see if you can see red through the lines.
4. Blood vessels relax allowing more blood to the surface so that heat can be lost to maintain your internal body temperature.

Such evidence questions can confirm student understanding of the causal relationships and enable students to reconsider their claims about causality.

HOW CAN QUESTIONS BE INTEGRATED INTO PROBLEM-SOLVING LEARNING ENVIRONMENTS?

In PSLEs, questions may be inserted in any kind of case to guide interpretation or inferences from the case, or they may be used to guide comparisons between cases. Questions may also form the cognitive model for cases in the form of an "ask system," where access to case information requires navigating an interrogative interface. Questions may also be used as guides for helping students learn to generate their own questions and use them to engage in reciprocal teaching among groups of students. An implicit goal of any kind of questioning is the ability of the learner to generate pertinent questions when the inserted questions are faded.

How Do You Insert Question Prompts?

The simplest method for asking questions is to insert them in instructional materials. Questions may be inserted in PSLEs before the students begin studying the problem, at the point of need, or after some form of instruction. Inserting questions prior to beginning solving a problem functions as an orienting device, cueing learners to important information or ideas to attend to. Questions may also be inserted into learning environments at the point of need. This placement would comprise a just-in-time support aimed at helping students to understand important issues. Finally, questions may be inserted following any learning activity as a summarizing or synthesizing activity. Although there exists a rich research literature on inserted or adjunct questions conducted mostly in the 1960s and 1970s, most of that research focused on improving reading comprehension during text processing (e.g., Rickards & Denne, 1978). While that research showed negative effect for factual prequestions, higher-order adjunct questions led to improved performance on repeated, related, and unrelated higher-order test questions (Hamaker, 1986). The effects of different levels of inserted questions on problem solving under different types and structures of problems deserves to be researched more. One of the big limitations in this research is that the structural characteristics of the problem spaces used are rarely characterized enough to understand the findings.

How Do You Design Ask Systems to Model Reflection-in-Action?

An ask system is a simple form of artificial-intelligence system that is used to structure access to information in multimedia hypertext and PSLEs. In effect, an ask system simulates a conversation with an experienced practitioner or effective tutor, where the user accesses information in response to an interrogative interface. That is, when students access an environment, they see a series of questions. Because experienced practitioners are often hard to locate and schedule time with, an ask system can be made available anytime and anywhere via the Internet. Ask systems may also be used to model reflection-in-action (Schön, 1983), where the questions mimic the kinds of reflective thinking that an experienced practitioner would engage in while solving a problem. In essence, ask systems provide a cognitive apprenticeship framework in which the learner assumes the role of the apprentice and the ask system acts as an expert.

Although reports on the impact of ask systems are rare (Ferguson, Bareiss, Birnbaum, & Osgood, 1992; Fitzgerald & Wisdo, 1994), ask-system design provides an ideal framework guiding students analysis and understanding of cases as problems to solve, case studies, cases as alternative perspectives, and cases as prior experiences. Ask systems are especially applicable for accessing and analyzing cases as problems to solve.

As part of a large project for training radiation-protection workers, we have developed an ask-system interface to problems in each of six different courses. As part of a course entitled Radiological Safety and Response, we developed fourteen modules that are accessed through the ask system. Table 18.1 describes the kinds of questions that orient each module. Figure 18.1 illustrates how the ask system is implemented. The ask system resides in the left-hand area of the Web interface and consists of questions that learners may ask about an authentic work problem. Learners learn how to think about and solve the problem by accessing information using the ask system.

Ask systems may also be used as performance support systems to help learners develop alternative solutions to problems. Figure 18.2 illustrates an ask system that was developed to aid students learning how to run a committee meeting in order to build consensus on a set of actions. This example shows how ask systems can be used to model problem-solving processes. Table 18.2 displays the two-level structure

Table 18.1
Example ask system for Radiological Safety and Response course

What caused this event?
Were communication errors involved?
Were judgment errors involved?
Were controls sufficient?
Were skills and training adequate?
Were performance errors involved?
Were equipment malfunctions involved?
How should I respond to this event?
What source(s) is of most concern and why?
How do I determine radiation and contamination levels?
What procedures apply to controlling this source(s)?
What equipment is needed?
What processes are involved in responding to this event?
How do I maintain ALARA while responding to this event?
How could this event be prevented?
What lessons were learned from this event?
Which error prevention tools could have prevented this event?
What corrective actions should be taken?
What guidelines, regulations, and/or standards apply?

Radiation Protection Technician Curriculum

"Learning through practice"

Radiological Safety and Response - Sealed and contained sources - **Exposure of radiography personnel due to source malfunction**

Ask a question!

What caused this event?

How should I respond to this event?

- What source(s) of radiation is of most concern and why?
- How do I determine radiation and contamination levels?
- What procedures apply to controlling this source(s) of radiation?
- What equipment is needed?
- What processes are involved in responding to this event?
- How do I maintain ALARA while responding to this event?

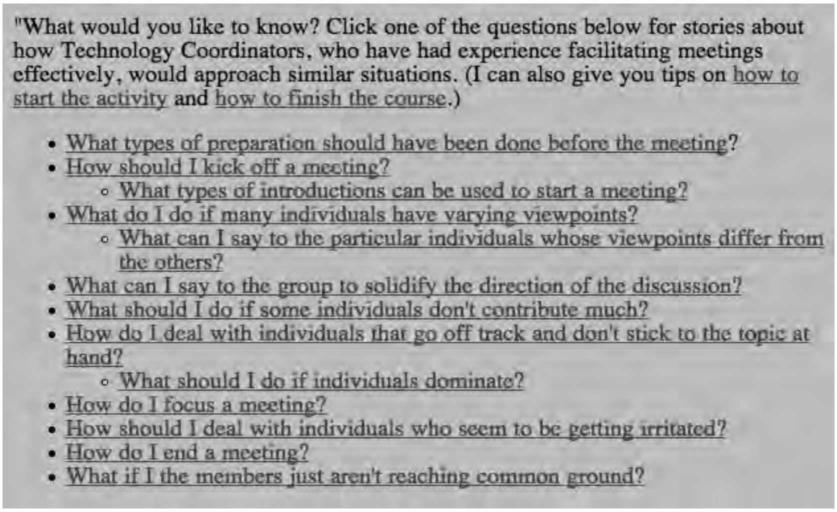
How could this event be prevented?

What processes are involved in responding to this event?

During the debriefing with AIRL, Mark, the on-shift Jackson RP Supervisor asked Gerry, a plant radiation protection technician (RPT), to immediately survey the area where the foreign object was located. Gerry quickly surveyed the object using the extendable pole survey meter and determined that the foreign object was the radiography source capsule. He immediately notified the control room and Mark. A plant announcement was made directing all plant personnel to evacuate the turbine building due to an unshielded radiography source. Additional on-shift RPTs with alarming electronic dosimeters and portable survey meters were directed to post the area around the source capsule. The boundary was located at the point where the radiation doses were less than 1 mrem/hr (10 µSv/hr) and radiation area signs and restricted area signs were hung on the boundary to alert plant personnel. Plant security personnel were also posted at the boundary to ensure that other workers would not enter the area.

Posted warning signage at the boundary of a high radiation area.

Figure 18.1 Radiation Protection Technician Curriculum ask system.



"What would you like to know? Click one of the questions below for stories about how Technology Coordinators, who have had experience facilitating meetings effectively, would approach similar situations. (I can also give you tips on how to start the activity and how to finish the course.)

- What types of preparation should have been done before the meeting?
- How should I kick off a meeting?
  - What types of introductions can be used to start a meeting?
- What do I do if many individuals have varying viewpoints?
  - What can I say to the particular individuals whose viewpoints differ from the others?
- What can I say to the group to solidify the direction of the discussion?
- What should I do if some individuals don't contribute much?
- How do I deal with individuals that go off track and don't stick to the topic at hand?
  - What should I do if individuals dominate?
- How do I focus a meeting?
- How should I deal with individuals who seem to be getting irritated?
- How do I end a meeting?
- What if I the members just aren't reaching common ground?

Figure 18.2 Ask system for PBLE on running a meeting.

of an ask system designed to provide engineering faculty members assistance on how to improve their teaching. The professors highlight the top-level question first. They are then redirected to the list of the second-level questions that enable faculty members to refine their

Table 18.2
Structure of ask system for engineering faculty

- How do I get my students to ask me questions?
  - What questioning strategies will encourage my students to participate during class time?
  - How do I get my students to ask the kinds of questions I think they should?
  - Why would I want students to participate more during class time?
  - What questioning strategies will facilitate critical thinking skills?
- How do I find out if my students understand what we are covering in class?
  - How do I get more students involved in in-class discussions?
  - How do I review previous instructional content?
  - How do I make connections with new material to previously learned material?
- What would make my lectures more effective?
  - How do I get students to be more attentive?
  - How do I get my points across more clearly during lecture?
  - How do I determine the effectiveness of lecture time?
  - Why might I be interested in what students think about lectures?
  - What would make my large lecture class more engaging?
  - What kinds of activities might I implement to deliver my content?
- How do I develop students' interest in the instructional material?
  - How do I get students to see the importance of what I'm teaching them?
  - How can I get my students to see the relationship between the theoretical and the real-world?
  - How can I increase the number of students who "get" what I'm teaching them?
  - How can I help students apply what I'm teaching them to real-life problems?
- How can I get students to be more successful on exams and their homework?
  - How do I get my students to remember what I'm teaching them?
  - How do I help my students to better understand the concepts behind the problems they solve in class and on homework?
- How can I get students to be able to solve problems on their own?
  - How can I get students to take the skills they learned from an in-class example and apply them to another problem?
  - How can I find out if students really understand the problem solving I do in class?
  - What kinds of activities could I implement to help students solve problems?
  - How do I get my students to solve a problem in multiple ways?
- What technologies are available to me that might help me in the classroom?
  - How can I use technology to help my students learn better?
  - What kind of technology would help me be more efficient in the classroom?
  - What technologies exist that would facilitate and/or enhance learning?
- How can I get my students to remember more of what I teach them?
  - How do I review previous instructional content?
  - What teaching strategies motivate students to become actively engaged?
  - How do I make connections with new material to previously learned material?
  - How would I get my points across more clearly during lecture?

search for teaching tips. These systems enable learners to analyze and address the problem they are trying to solve.

Within the ask system, knowledge is not constructed by the system or based on theoretical domain representations; rather, the learner actively constructs knowledge by interfacing with the system, thus affording a learner-centric mode of knowledge acquisition within authentic contexts of real-world scenarios (Bareiss & Osgood, 1993; Fitzgerald & Wisdo, 1994). The ask system enables learners to access answers from an experienced practitioner to questions in much the same way as they would in the context of completing an apprenticeship, that is, by asking questions (Johnson, Birnbaum, Bareiss, & Hinrichs, 1998). At a basal level, an ask system attempts to emulate a conversation with an expert (Bareiss & Osgood, 1993). This conversation is conducted between learners and the system by means of dialogues in which the learner selects from a constrained set of questions within the system, and the system responds with pertinent answers couched within stories (Ferguson et al., 1992). The answers to the questions were obtained from extensive interviews with experienced practitioners and are presented in the form of thirty-second to two-minute long video clips, as well as in plain text with associated multimedia components (graphics, diagrams, etc.).

While ask systems have not been extensively researched, there is good reason to predict that different ask-system structures can influence students' thinking about problems in productive ways.

How Do You Stimulate Reciprocal Questioning?

Guided reciprocal peer-questioning has been used extensively for learning lecture and text materials. It is based on the concept of reciprocal teaching (Palinscar & Brown, 1984), where the tutor and students take turns leading a dialogue focused on important features of the text. In reciprocal teaching, an adult model guides the student to interact with the text in more sophisticated ways, which leads to an improvement in the quality of the summaries and questions. In reciprocal questioning, the teacher or learning environment provide generic question prompts that guide student questioning of each other. Students take turns posing questions based on instructor-provided generic questions to guide their own question asking. Generic question prompts include:

- How would you use . . . to . . . ?
- What is a new example of . . . ?

- Explain why . . .
- What do you think would happen if . . . ?
- What is the difference between . . . and . . . ?
- How are . . . and . . . similar?
- What is a possible solution to the problem of . . . ?
- What conclusions can you draw about . . . ?
- How does . . . affect . . . ?
- In your opinion, which is best, . . . or . . . ? Why?
- What are the strengths and weakness of . . . ?
- How is . . . related to . . . that we studied earlier?

Groups that trained in this way asked more critical thinking (vs. recall) questions, gave more explanations (vs. low-level elaboration responses) and had higher achievement than students instructed to discuss lecture (King, 1990).

Similarly, students in the guided questioning treatment gave significantly more explanations and received significantly more explanations in response to their questions than did students without guided questions.

In a follow-up study, King (1994) added question prompts to assess prior knowledge and connect that personal knowledge to lesson material. Connection questions included:

- Explain why . . .
- Explain how . . .
- How are . . . and . . . similar/different?
- What are strengths and weakness of . . . ?

Prior knowledge questions included:

- Describe . . . in your own words.
- What does . . . mean?
- Why is . . . important?
- How could . . . be used to . . . ?
- What would happen if . . . ?
- How does . . . tie in with . . . that we learned before?

Students who asked these prior knowledge and connections questions engaged in higher-level verbal interactions. The reciprocal questioning research clearly shows that students can learn to generate and ask more sophisticated questions of each other, which in turn prompts more elaborate explanations of material being studied.

How Do You Teach Students to Ask Questions?

As argued before, asking questions is integral to understanding. The metacognitive goal of any kind of questioning is to facilitate students' abilities to generate and answer meaningful questions on their own. This is important because students who know more ask better questions. While reading scientific passages, more knowledgeable eighth- to twelfth-grade students asked more questions (Costa, Caldeira, Gallastegui, & Otero, 2000), such as:

- Why can fish not break the water molecule?
- What does it mean to break a molecule?
- What are the bonds that link oxygen to hydrogen?
- Why are oxygen and hydrogen linked by strong bonds?
- Why does pollution cause a decrease in oxygen?
- Why do fish die from asphyxia?
- Why are oxygen and others soluble in liquids?
- How is it possible to dissolve oxygen in water?

The quality of student-generated questions is the strongest predictor of domain knowledge and problem solving (Graeser & Olde, 2003). Good comprehenders implicitly ask more explanatory reasoning questions (why, how, what-if, what-if-not, what consequences) when they study written and spoken discourse. Notice that most of these questions are causal (see Chapter 17). The point is that students can be taught effectively to ask meaningful questions. When students are taught to generate questions about material they read, they perform better on tests (Rosenshine et al., 1996). In another study, students were trained to use a self-questioning procedure to process information presented in a lecture (King, 1989). The self-questioning strategies significantly improved comprehension. These results suggest that practice in this self-questioning information-processing procedure can effectively improve college students' comprehension of lectures.

Question generation can also affect problem solving. When students generated more questions while solving ethics problems, they produced better argumentative essays. When information was accessed through questions, students generated more questions about problem solving (Jonassen, Shen, Marra, Cho, Lo, & Lohani, 2009). However, the role of self-generated questions on problem solving needs much more research.

Do Students Need to Explicitly Answer Questions?

Although many studies have supported the use of questions to guide student thinking while studying, a fundamental issue remains. How do we know that the students actually think about the questions? That is, is asking the question in a PSLE sufficient for engaging the cognitive activity addressed in the question? A recent unpublished study showed that students who were required to write answers to the questions performed better than students who were only prompted, and several students in the question-only condition skipped the question prompts. Surprisingly little research has focused on this issue. For purposes of traditional study strategies, it makes sense that requiring written responses will ensure deeper level thinking. However, requiring written responses raises further issues about the nature and timing of feedback provided to the students about their responses.

Most of the research on inserted questions studied the effects of the questions on examination behavior. No one has examined the effects of written responses in PSLEs. Will the desire to solve a problem provide sufficient motivation to ensure meaningful responses to questions inserted to scaffold student thinking? Or should students be required to provide written responses in order to engage the kind of thinking needed to solve the problem? How can discussion groups be used to ensure meaningful responses to scaffolding questions? All of the questions deserve further research.

19

MODELING PROBLEMS

WHY SHOULD STUDENTS CONSTRUCT MODELS?

"Scientific practice involves the construction, validation, and application of scientific models, so science instruction should be designed to engage students in making and using models" (Halloun & Hestenes, 1987, p. 455). The same assumption applies to all disciplines. Constructing models of phenomena being studied is perhaps the most powerful strategy in support of meaning making. In this chapter, I demonstrate how important modeling is to problem solving. One of the most powerful methods for clarifying the nature of a problem is to construct a model of it. In Chapter 7, I described how designers necessary construct increasingly complex models of the designs that they are working on.

There are many rationales for engaging students in modeling what they are learning. The underlying assumption of my work in Mindtools (Jonassen, 1996, 2000a, 2006a) is that building models of phenomena being studied necessarily engages critical thinking about the ideas as well as contributing significantly to conceptual change. Mindtools are computer applications such as concept mapping, databases, expert systems, and systems-modeling tools that can be used by students to construct semantic models of any discipline or topic being studied. When students use these tools to construct models, they are learning *with* the computer, not *from* it. Computers become intellectual partners that support learning by helping learners to articulate and represent what they know (not what the teacher knows) and for reflecting on what they have learned and how they came to know. Because each tools requires students to represent what they know in different ways, the tools amplify student thinking. Modeling is fundamental to human cognition and scientific inquiry. Modeling helps learners to express and externalize their thinking; to visualize and test components of their theories; and to make materials more interesting. Models function as epistemic resources (Morrison & Morgan, 1999). We must first understand what we can demonstrate in the model before we can ask questions about the real system. In summary, if you are unable to model ideas or problems, then you do not understand them.

Building models using different qualitative and quantitative formalisms embedded in different kinds of modeling tools is among the most conceptually engaging classroom activities possible that has the greatest potential for engaging and encouraging conceptual change processes (Jonassen, 2008b). Modeling is an important method for engaging conceptual change (Nersessian, 1999). Building explicit models externalizes or reifies mental models or personal theories, thereby fostering conceptual change. When a student builds a model and the model fails to deliver expected results, cognitive conflict occurs, ushering in conceptual change. Another important reason for modeling is the evaluation of alternative models, that is, the comparison of two or more models for their relative fit to the world (Lehrer & Schauble, 2003). Comparing and evaluating models requires understanding that alternative models are possible and that the activity of modeling can be used for testing rival models. Recognizing the existence of competing models is essential to conceptual change.

There are many reasons for constructing models to support meaningful learning and problem solving:

- Model building is a natural cognitive phenomenon. When encountering unknown phenomena, humans naturally begin to construct personal theories about those phenomena that are represented as informal models.
- Modeling is quintessentially constructivist—constructing personal representations of experienced phenomena.
- Modeling supports hypothesis testing, conjecturing, inferring, and a host of other important cognitive skills.
- Modeling requires learners to articulate causal reasoning (see Chapter 17), the cognitive basis for most scientific reasoning.
- Modeling engages conceptual change.

- Modeling results in the construction of cognitive artifacts (externalized mental models).
- When students construct models, they own the knowledge. Student ownership is important to meaning making and knowledge construction.
- Modeling supports the development of epistemic beliefs.

Epistemologically, what motivates our efforts to make sense of the world? According to Wittgenstein (1953), what we know is predicated on the possibility of doubt. We know many things, but we can never be certain that we know it. Comparing and evaluating models can be used for testing rival models (Lehrer & Schauble, 2003).

WHY MODEL PROBLEMS?

A large number of studies have documented learners' inability to transfer problem-solving skills, especially for well-structured problems. This failure is often attributed to poorly constructed problem schemas (Chapter 15). Students are unable to solve structurally identical problems because they immediately search for the correct equation to use and because they focus on surface features of the problems rather than developing adequate conceptual understanding of the problem domain (Gick & Holyoak, 1980, 1983; Reed, 1987), a failure in analogical reasoning (Chapters 11 and 16). Even instructional programs in critical thinking related to problem solving have failed to show evidence of problem-solving transfer (Chipman, Segal, & Glaser, 1985; Nickerson, Perkins, & Smith, 1985). Why are students unable to transfer skills in problem solving?

Perhaps the primary reason that problem solving fails is because in most educational contexts, students represent problems in only one way, in most cases quantitatively with an equation (also described in Chapter 2). This form of problem solving typically involves reading a well-structured story problem, attempting to identify the correct equation, inserting values from the problem statement into the formula, and solving for the unknown value, known as the direct translation strategy. Unfortunately, it is the unsuccessful problem solvers who base their solution plans on the numbers and keywords that they select from the problem (Hegarty, Mayer, & Monk, 1995). A primary assumption of this chapter is that relying exclusively on a quantitative (or any single) form of representation restricts student's understanding of the problem and its relationship to domain knowledge. In order to be able to transfer problem-solving skills, students must develop conceptual understanding of how problems relate to domain knowledge, and that requires that students learn to represent their understanding in more than one way. How does this work?

In order to develop this required conceptual understanding, it is necessary for students to understand the internal connections between problems and disciplinary knowledge in order to transfer skills (Singly & Anderson, 1989). That is, their mental models of their disciplines must be multi-modal and include problems as part of their structure. Well-developed mental models consist of multiple mental representations, including structural knowledge, procedural knowledge, reflective knowledge, images and metaphors of the system, of strategic knowledge as well as social/relational knowledge, conversational/ discursive knowledge and artifactual knowledge (Jonassen & Henning, 1999). The more ways that learners are able to represent problems in relation to disciplinary knowledge, the better able they will be to transfer their skills. Ploetzner and Spada claim that "the ability to construct and coordinate qualitative and quantitative problem representations is a precondition for successful and efficient problem solving in physics" (1998, p. 96). Qualitative and quantitative representations are complementary. Ploetzner, Fehse, Kneser, and Spada (1999) showed that when solving physics problems qualitative problem representations are necessary prerequisites to learning quantitative representations. That claim is supported by Bodner (1991), Schoenfeld (1992), and Hestenes (1997). Qualitative representation is a missing link in novice problem solving (Chi, Feltovich, & Glaser, 1981; Larkin, 1983). When students try to understand a problem in only one way, especially when that way conveys no conceptual information about the problem, students do not understand the underlying systems they are working in. So, it is necessary to support conceptual understanding in students before solving problems by helping them to construct a qualitative representation of the problem as well as a quantitative one. Qualitative problem representations both constrain and facilitate the construction of quantitative representations (Ploetzner & Spada, 1998). Qualitative problem representation is the key to problem solving.

Why should students use different tools to model problems? One important reason is that those tools are related to authentic practice. Practicing engineers, for example, use multiple forms of problem representation, such as drawing, spreadsheets, computer-assisted design documents, mathematical models, and so on (Jonassen, Strobel, & Lee, 2006). Another rationale for using tools to scaffold problem representations is the distribution of cognitive responsibility. Zhang and Norman (1994) developed a theoretical framework for distributing representations internally and externally. They consider the internal and external representations as equal partners in a representation system, each with separate functions. For example, external representations, Zhang and Norman claim, activate perceptual processes while internal representations activate cognitive processes. Together, the representations are symbiotic. A key assumption of problem solving, according to Zhang (1997) is that external representations need not necessarily be re-represented as an internal representation in order to be used for problem solving. They can directly activate perceptual operations and cognitive activities provided by the problem solver. These external representations cannot function independently without the support of internal perceptions or cognitions.

WHAT ARE MODELS?

There are numerous kinds of models that can be used to represent phenomena in the world or the mental models that learners construct to represent them. Mathematicians and scientists most often refer to computational models using mathematical formalisms (e.g., calculus, differential equations, Bayesian probabilities). Data models are only one kind of model. Harris (1999) describes three kinds of models:

1. data models;
2. theoretical models;
3. experimental models.

Theoretical models are abstract representations of systemic elements or factors, while experimental models are designed to test the theoretical models. They are more specific than theoretical, including:

- directives for action;
- specifications of the size of sample populations;
- definitions of experimental variables and test statistics;
- measures for comparing hypotheses and observed values.

Their purpose is to predict or specify the kind of data that we are looking for and to specify analytical techniques for linking data to questions. Lehrer and Schauble (2003) describe a continuum of model types including physical models, representational systems (grounded in resemblance between the model and the world), syntactic models (summarizing essential functioning of system), and hypothetical-deductive models (formal abstractions). Whatever they are, models qualitatively, functionally, or formally represent the real objects under study (Yu, 2002).

Models are conceptual systems consisting of elements, relations, operations, and rules governing interactions that are expressed using external notation systems and that are used to construct, describe, or explain the behavior of other systems (Lesh & Doerr, 2003). The models that are constructed by learners using equations, diagrams, and computer programs represent the models that exist in the minds of problem solver. That is, there are models in the mind (mental models) and there are models in the world that are constructed by learners. Both of these kinds of models reflect phenomena in the world. The relationship between internal and external models is not well understood, but there is good reason to believe that there is a dynamic and reciprocal relationship between internal mental models and the external models that students construct. The mental models provide the basis for external models. The external models in turn constrain and regulate internal models, providing the means for conceptual change.

We learn from models by using them and by building them (Morgan, 1999). What we can learn from using models, however, depends on the extent to which we can transfer the things we learn from manipulating the model to our theory or the real world. Learning from building models involves finding out what elements fit together in order to represent the theory or the world or both. Modeling requires making certain choices, and it is in these choices that the learning process lays. "We do not learn much from looking at a model—we learn a lot more from building the model and from manipulating it" (Morrison & Morgan, 1999, pp. 11–12).

HOW CAN PROBLEMS BE MODELED?

Experts are better problem solvers than novices for several reasons. Perhaps the most important reason is that they construct richer, more integrated mental representations of problems than do novices (Chi et al., 1981; Chi & Bassock, 1991; de Jong & Ferguson-Hessler, 1991; Larkin, 1983). Experts are better able to classify problem types (Chi et al., 1981; Chi & Bassock, 1991) because their representations integrate disciplinary knowledge with problem types. However, researchers and theorists differ in their claims about the forms in which experts represent problems. Anderson (1983) claims that problems are represented as production rules, whereas Chi and Bassock (1989) and Larkin (1983) believe that they are schema-like forms. Whatever form, it is generally accepted that problems solvers need to construct some sort of internal representation (mental model) of a problem (problem space) in order to solve a problem. Personal problem representations serve a number of functions (Savelsbergh, de Jong, & Ferguson-Hessler, 1998):

- To guide further interpretation of information about the problem.
- To simulate the behavior of the system based on knowledge about the properties of the system.
- To associate with and trigger a particular solution schema (procedure).

Problem representation is the key to problem solving among novice learners as well as experts. Instruction must help learners to construct problem representations that integrate their problem representations with domain knowledge. What characterizes good problem representations? The quality of internal problem representations is a function of the coherence (internal structure) and the integration of the different representations (qualitative and quantitative, abstract-concrete, visual verbal). What makes experienced problems solvers more effective is their richer, more coherent and interconnected representations of problems.

HOW DO STUDENTS MENTALLY REPRESENT PROBLEMS?

Although it is widely assumed that problem solvers usually perform a task by using the external representation of the problem as given, other researchers have focused on the processes of mapping problem elements in the construction of personal, mental problem representations. “Problem solving must begin with the conversion of the problem statement into an internal representation” (Reimann & Chi, 1989, p. 165). Most psychologists believe that “there exists an early holistic or gestalt stage in problem solving in which students must disembed relevant information from a question and restructure the problem” (Bodner & McMillen, 1986, p. 735). That “representation, by definition, is the specification of these objects, operators, and constraints, as well as the initial and final states” (Reimann & Chi, 1989, p. 165).

Why is problem modeling so important? Meaningful problem solving is impossible without connecting the problem to disciplinary understanding. In order to do so, learners must relate the original problem presentation to construct a meaningful internal representation that can be manipulated (Larkin, 1985). In a series of experiments, Kotovsky and Fallside (1989) demonstrated that problem-solving transfer depends on the internal representation of problems. Internal representations can then function, they believe, independently of the stimulus features of the problem, which contradicts the assumptions of researchers focusing on the external problem representations. By evoking particular internal problem representations, we can increase the likelihood that those representations will produce positive transfer.

Mental problem representation is also important because individuals choose to represent problems in ways that make more sense to them. For instance, Jones and Schkade (1995) found that a substantial proportion of analysts use different representations of problems than those they were presented. That is, they translate problems from the given external representation to one that is more familiar or convenient. Rather than uniformly identifying and representing core issues in design problem spaces, Goldschmidt (1989) found that architectural designers interpreted and attended to remote and diverse issues and generated very idiosyncratic problem representations.

WHAT TOOLS CAN BE USED FOR MODELING PROBLEMS?

Successful problem solving requires learners to construct mental models of problems. In this section, I demonstrate how students can use computer-based tools to externalize those internal mental models. When students use different knowledge representation formalisms (i.e. knowledge representation tools, aka cognitive tools or Mindtools) to represent problems (the specific problem embedded in domain knowledge), they understand the problem metter and are more capable of generating and testing solutions.

How Can Concept Maps Model Problems?

Concept maps are spatial representations of concepts and their interrelationships (propositions) that are intended to represent the knowledge structures that humans store in memory (Jonassen, Beissner, & Yacci, 1993). These knowledge structures are also known as cognitive structures, conceptual knowledge, structural knowledge, and systemic knowledge. They are useful for our purpose because internal problem representations can be represented as semantic nets (Larkin, 1985). Concept maps are graphs consisting of nodes representing concepts and labeled lines representing relationships among them. Figure 19.1 illustrates a semantic network about stoichiometry problems that are solved in introductory chemistry courses. These are the concepts and relationships among them that underlie any molar conversion problems. Understanding those concepts and relationships is essential for being able to solve chemistry problems and to understand what it means to solve those problems. Concept maps may also be used to model more complex and ill-structured problems. While working on solutions to the SARS epidemic that plagued the world some years

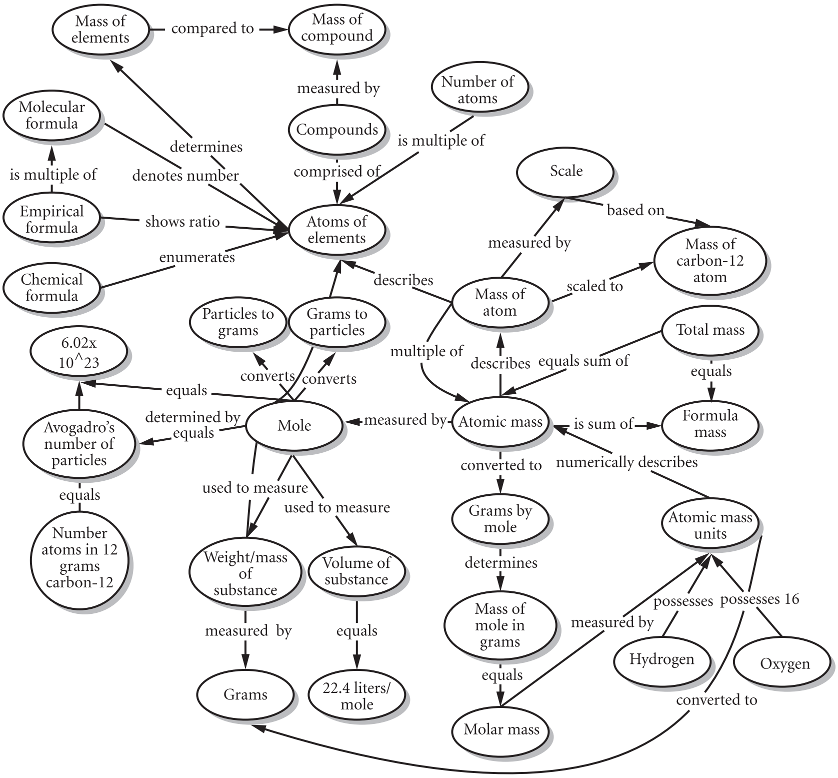
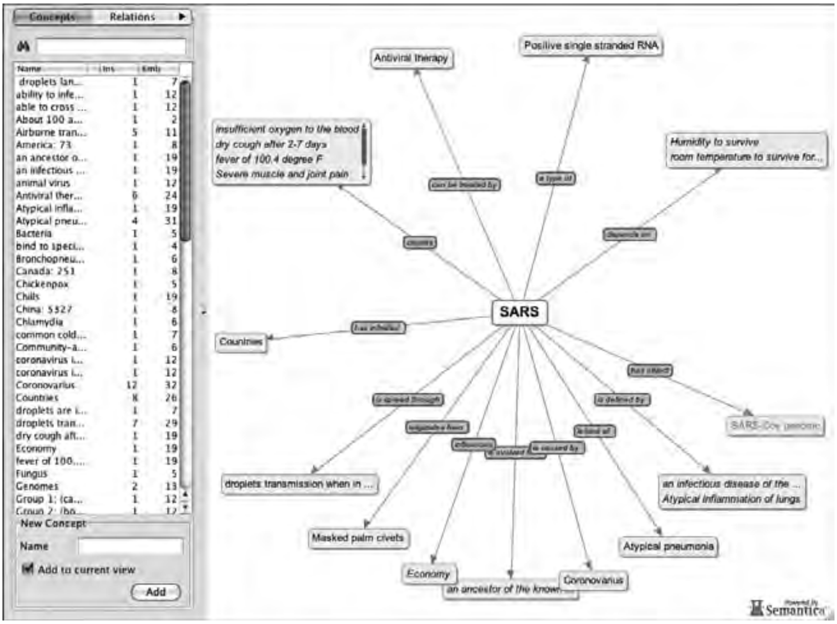


Figure 19.1 Semantic network (concept map) of ideas in stoichiometry in chemistry.

ago, students constructed a complex semantic net of SARS (one screen of which is displayed in Figure 19.2). When students construct concept maps, they are required to isolate the most important concepts in a problem domain, assemble those concepts into nodes, and link the nodes and determine the semantic nature of the link between the nodes. In doing so, they reconceptualize the content domain by constantly using new propositions to elaborate and refine the concepts that they already know. More importantly, concept mapping increases the quantity of formal content knowledge because it facilitates learners to use the skill of searching for patterns and relationships among concepts (Slack & Stewart, 1990). Research has shown that well-organized and integrated domain knowledge (as evidenced by integrated concept maps) is essential for problem solving. It is necessary to understand the conceptual relationships between the concepts in any problem domain in order to be able to transfer any problem-solving skills developed.



Name	Ins	Emb
droplets lan...	1	7
ability to infe...	1	12
able to cross ...	1	12
About 100 a...	1	2
Airborne tran...	5	11
America: 73	1	8
an ancestor o...	1	19
an infectious ...	1	19
animal virus	1	12
Antiviral ther...	6	24
Atypical infla...	1	19
Atypical pneu...	4	31
Bacteria	1	5
bind to speci...	1	4
Bronchopneu...	1	6
Canada: 251	1	8
Chickenpox	1	5
Chills	1	19
China: 5327	1	8
Chlamydia	1	6
common cold...	1	7
Community-a...	1	6
coronavirus i...	1	12
coronavirus i...	1	12
Coronovarius	12	32
Countries	8	26
droplets are i...	1	7
droplets tran...	7	29
dry cough aft...	1	19
Economy	1	19
fever of 100....	1	19
Fungus	1	5
Genomes	2	13
Group 1: (ca...	1	12
Group 2: (bo...	1	12

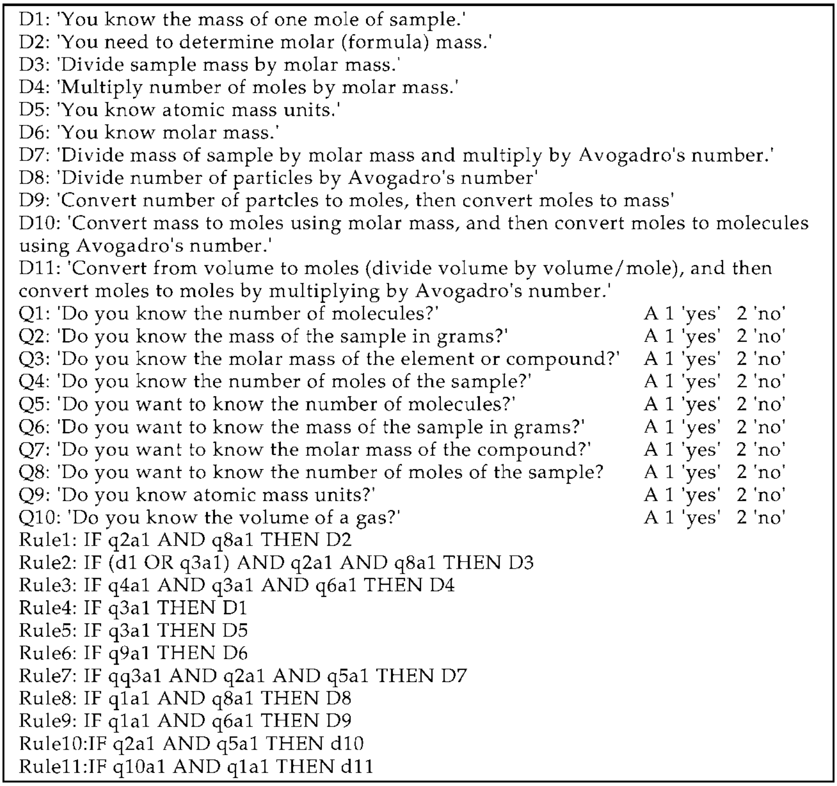
Figure 19.2 Single frame from a complex concept map on SARS.

How Can Expert Systems Be Used to Represent Problems?

Expert systems represent an artificial-intelligence paradigm designed to simulate expert reasoning in support of decision making for any kind of problem. Expert systems include a knowledge base of facts about objects and if-then rules about the relationships among those objects that can qualitatively represent covariational and mechanistic information about causal relationships (see Chapter 17). Like a human expert, an expert system (computer program) is approached by an individual (novice) with a problem. The system queries the individual about the nature of the problem and then searches the rule base to provide advice. Rules state that IF a set of conditions exists, THEN some conclusion is reached. For example, IF temperature increases, THEN pressure increases. Conditions can be combined using conjunctions (condition 1 AND condition 2 must exist), disjunctions (condition 1 OR condition 2 must exist), and negations (condition 1 but NOT condition 2 must exist) in order to reach a conclusion about a set or causal relationships. That conclusion may be an action or it may state another condition, which is then combined with other conditions to reach another decision.

Building expert systems is a knowledge-modeling process that enables experts and knowledge engineers to construct models of causal reasoning processes (Adams-Webber, 1995; see also Chapter 17), essential components of problem solving. Production-rule models used in expert systems are the best representation of procedural knowledge. Figure 19.3 illustrates part of a rule base predicting the results of stoichiometry problems.

Expert systems may also be used to reflect on far more vexing problems. The rule base in Figure 19.4 was produced by students of World War II, who attempted to represent the reasoning that Truman may have used in deciding whether or not to drop an atomic bomb on Hiroshima. Although the content is gruesome and many factors were not considered, it describes a deeper reflection on historical problems than the typical memorization of names, dates, and places. In this kind of rule base, the decisions are usually stated first. This requires that the students identify the goals before clarifying any of the decision factors. Next the designer identifies the decision factors in the form of questions



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D1: 'You know the mass of one mole of sample.'
D2: 'You need to determine molar (formula) mass.'
D3: 'Divide sample mass by molar mass.'
D4: 'Multiply number of moles by molar mass.'
D5: 'You know atomic mass units.'
D6: 'You know molar mass.'
D7: 'Divide mass of sample by molar mass and multiply by Avogadro's number.'
D8: 'Divide number of particles by Avogadro's number'
D9: 'Convert number of partcles to moles, then convert moles to mass'
D10: 'Convert mass to moles using molar mass, and then convert moles to molecules
using Avogadro's number.'
D11: 'Convert from volume to moles (divide volume by volume/mole), and then
convert moles to moles by multiplying by Avogadro's number.'
Q1: 'Do you know the number of molecules?'                  A 1 'yes'  2 'no'
Q2: 'Do you know the mass of the sample in grams?'          A 1 'yes'  2 'no'
Q3: 'Do you know the molar mass of the element or compound?' A 1 'yes'  2 'no'
Q4: 'Do you know the number of moles of the sample?'        A 1 'yes'  2 'no'
Q5: 'Do you want to know the number of molecules?'          A 1 'yes'  2 'no'
Q6: 'Do you want to know the mass of the sample in grams?'  A 1 'yes'  2 'no'
Q7: 'Do you want to know the molar mass of the compound?'   A 1 'yes'  2 'no'
Q8: 'Do you want to know the number of moles of the sample? A 1 'yes'  2 'no'
Q9: 'Do you know atomic mass units?'                        A 1 'yes'  2 'no'
Q10: 'Do you know the volume of a gas?'                     A 1 'yes'  2 'no'
Rule1: IF q2a1 AND q8a1 THEN D2
Rule2: IF (d1 OR q3a1) AND q2a1 AND q8a1 THEN D3
Rule3: IF q4a1 AND q3a1 AND q6a1 THEN D4
Rule4: IF q3a1 THEN D1
Rule5: IF q3a1 THEN D5
Rule6: IF q9a1 THEN D6
Rule7: IF qq3a1 AND q2a1 AND q5a1 THEN D7
Rule8: IF q1a1 AND q8a1 THEN D8
Rule9: IF q1a1 AND q6a1 THEN D9
Rule10:IF q2a1 AND q5a1 THEN d10
Rule11:IF q10a1 AND q1a1 THEN d11
```

Figure 19.3 Excerpt from expert system rule base on stoichiometry.

that will be asked of the user. This is the essence of the design process. Writing questions that are simple enough for any novice user to be able to answer is difficult. With this expert system shell, the designer next writes the rules, using IF–THEN (Boolean) logic to relate the decisions to the decision factors or questions. The rule base in Figure 19.4 consists of twenty rules that comprise the heart of the knowledge base. For

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Decision 1: Atomic fission should only be used for peaceful purposes.
Decision 2: The atomic bomb should be used as quickly as possible, primarily on military targets.
Decision 3: Only knowledge of the weapon's existence should be used as a threat to induce Japan to surrender.
Decision 4: The atomic bomb should not be used, but research should be made known after the war ends.
Question 1: Do you want to encourage the Japanese to surrender as quickly as possible?
Answers 1 Yes
2 No.
Question 2:Do you want to limit the loss of Allied and Japanese lives?
Answers 1 Yes
2 No.
Question 3:Do you want to use the weapon against the Germans?
Answers 1 Yes
2 No
3 Unsure.
Question 4: Do you want to use the atomic fission research ONLY to create alternate sources of energy?
Answers 1 Yes
2 No
3 Unsure.
Question 5: Do you want to increase the political power of the Allies during and after the war?
Answers 1 Yes
2 No
3 Unsure.
Question 6: Do you believe the Japanese will surrender with continued conventional bombing of Japanese cities?
Answers 1 Yes
2 No
3 Unsure.
Question 7: Was the Manhattan Project (development of atomic fission) initially begun primarily for future military use?
Answers 1 Yes
2 No
3 Unsure.
Question 8: Do you want to end the Japanese march through Asia?
Answers 1 Yes
2 No
3 Unsure.
Question 9: Do you want to use atomic fission as only a psychological weapon?
Answers 1 Yes
2 No
3 Unsure.
Question 10: How much longer should the war continue (from Spring 1945)?
Answers 1 3 months
2 6 months
3 1 year
4 indefinitely.
Rule 1: IF Question1=Answer1 & Question2=Answer1 & Question5=Answer1 THEN Decision2.
Rule 2: IF Question3=Answer2 THEN Decision4.
Rule 3: IF Question4=Answer1 THEN Decision3.
Rule 4: IF Question4=Answer2 THEN Decision2.
Rule 5: IF Question5=Answer1 & Question6=Answer2 THEN Decision2.
Rule 6: IF Question6=Answer1 THEN Decision4.
Rule 7: IF Question6=Answer2 & Question1=Answer1 & Question8=Answer1 THEN Decision2.
Rule 8: IF Question6=Answer3 THEN Decision3.
Rule 9: IF Question7=Answer1 & Question1=Answer1 THEN Decision2.
Rule 10: IF Question7=Answer2 THEN Decision1.
Rule 11: IF Question7=Answer3 THEN Decision4.
Rule 12: IF Question8=Answer1 & Question6=Answer2 & Question1=Answer1 THEN Decision2.
Rule 13: IF Question8=Answer2 THEN Decision3.
Rule 14: IF Question9=Answer1 THEN Decision3.
Rule 15: IF Question9=Answer2 & Question8=Answer1 & Question7=Answer1 & Question1=Answer1 THEN Decision2.
Rule 16: IF Question4=Answer1 & Question5=Answer1 & Question7=Answer3 THEN Decision4.
Rule 17: IF Question10=Answer1 & Question2=Answer1 & Question6=Answer3 THEN Decision2.
Rule 18: IF Question10=Answer2 & Question3=Answer1 & Question5=Answer1 THEN Decision2.
Rule 19: IF Question10=Answer3 & Question6=Answer1 & Question8=Answer3 THEN Decision4.
Rule 20: IF Question10=Answer4 & Question4=Answer1 & Question6=Answer3 THEN Decision 4.

Figure 19.4 Expert system rule base on the reasoning for the atomic attack on Hiroshima.

example, the first rule states that IF the answer to Question 1 is yes AND the answer to Question 2 is also yes AND the answer to Question 5 is also yes, THEN the atomic bomb should be used as quickly as possible, primarily on military targets. The remainder of the rules specify alternative conditions that may have existed at that time.

Externalizing the predictions and inferences (Chapter 17) of a skilled problem solver requires the learners to think like the president, not like a student. Using expert system shell programs to construct the IF-THEN rule bases, novices can easily learn to build expert systems to reflect the procedural knowledge required to solve particular kinds of problems. These rule bases are qualitative representations of the causal reasoning that is implied in the formulae they use to solve the problems. Rather than representing problem solving as a series of steps, building expert systems requires learners to represent the causal

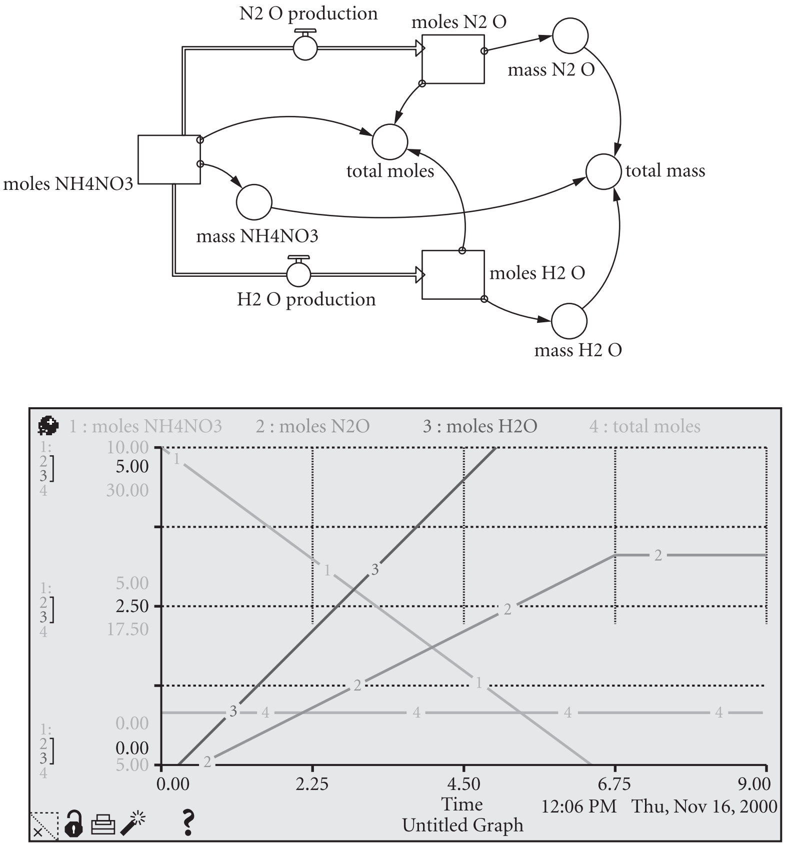


Figure 19.5 Systems model of stoichiometry problem.

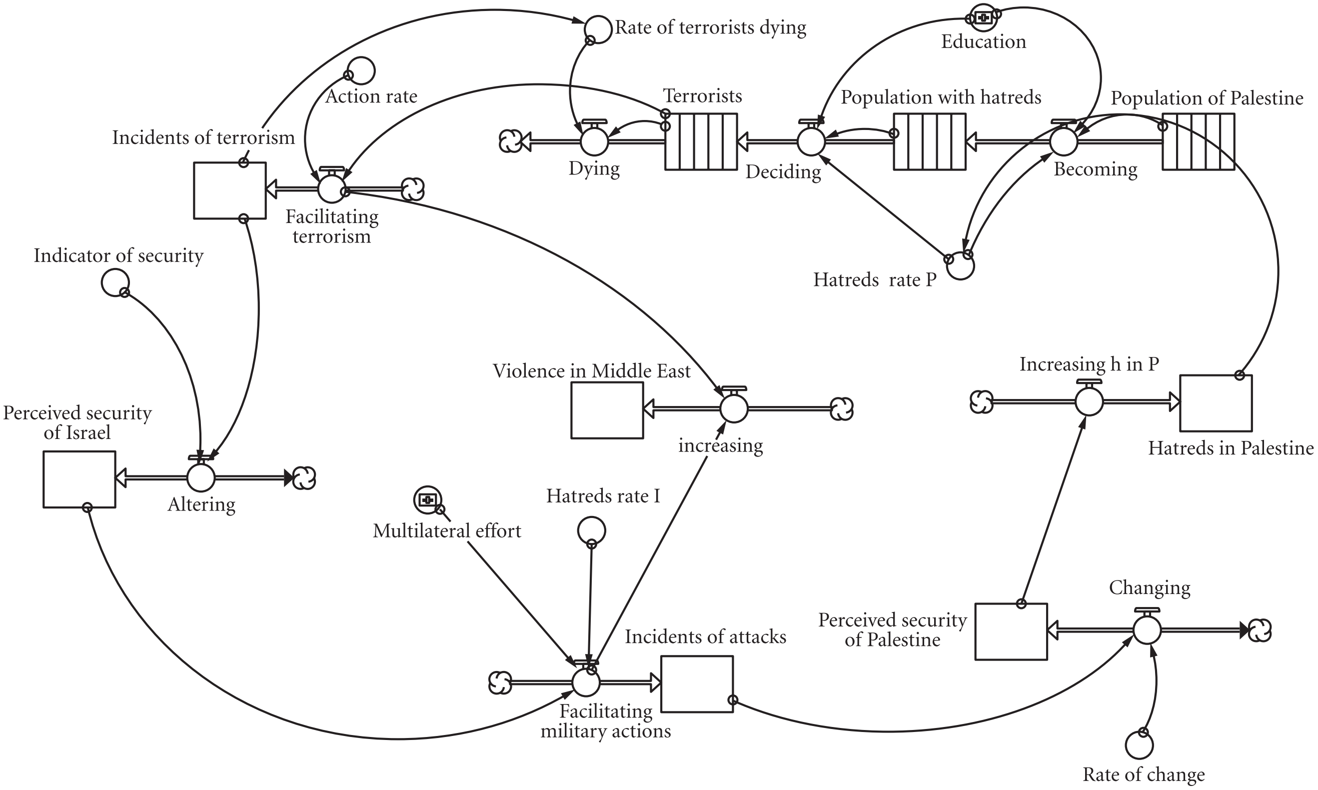


Figure 19.6 Systems dynamics model of Israeli–Palestinian conflict.

(predictive or inferential) reasoning that is required to solve the problem. Lippert (1987) found that the analysis of subject matter required to develop expert systems is so deep and so incisive that learners develop a greater domain comprehension, which is essential for problem solving.

How Can Systems-Modeling Tools Be Used to Represent Problems?

A systems model is a conceptual and conjectural representation of the dynamic relations among factors in a system, resulting in a simulation that imitates the conditions and actions of it. These dynamic simulation models represent the changing nature of systemic phenomena. Systems-modeling tools use a simple set of building block icons (stocks, flows, converters, and connectors) to map processes. Figure 19.5 illustrates a systems model of an actual stoichiometry problem.

Systems-modeling tools enable learners to run and test the model that they have created and observe the output in graphs, tables, or animations. In Figure 19.5, the model is in the upper part of the figure, while the output is illustrated in the lower part of the figure. Systems-modeling tools provide a powerful suite of tools for representing the complexity of dynamic systems. Being able to test your model makes systems-modeling tools a much more powerful tool for representing problems. They can also be used to model very ill-structured problems. For example, Figure 19.6 illustrates the beginning model produced by students trying to find a solution to the age-old Israeli–Palestinian conflict. By continuously testing and adapting the model to reflect the reality of the situation, these students gained better insights into the problem. Unfortunately, no empirical research has ever focused on the use of systems modeling to support problem solving or higher-order thinking. Systems modeling necessarily engages causal reasoning (Chapter 17) about dynamic systems. Because systems modeling supports strategic understanding of a problem, we believe that building systems models of problem types will support problem solving and transfer better than any other kind of tool. How much effect the construction of systems models will have on problem solving needs to be examined.

20

ARGUING TO LEARN TO SOLVE PROBLEMS

WHY LEARN TO ARGUE?

> It is in argument that we are likely to find the most significant way in which higher order thinking and reasoning figure in the lives of most people. Thinking as argument is implicated in all of the beliefs people hold, the judgments they make, and the conclusions they come to; it arises every time a significant decision must be made. Hence, argumentative thinking lies at the heart of what we should be concerned about in examining how, and how well, people think.
>
> (Kuhn, 1992, pp. 156–157)

Argumentation is the means by which we rationally resolve questions, issues, and disputes and solve problems. An argument consists of a claim (solution) that is supported by principles (warrants), evidence, and rebuttals against potential counterarguments (all of which are described later in this chapter). Fostering argumentation in problem-solving learning environments (PSLEs) promotes problem solving. As I will elaborate, arguing for alternative interpretations or solutions to problems is especially important when addressing ill-structured problems.

Science educators have become especially supportive of argumentation when learning and problem solving. They argue that argumentation is central to scientific thinking (Driver, Newton, & Osborne, 2000; Duschl & Osborne, 2002; Kuhn, 1993; Newton, Driver, & Osborne, 1999). Practicing scientists engage in argumentation in order to articulate and refine their own scientific knowledge (von Aufschnaiter, Erduran, Osborne, & Simon, 2008). When science is applied, the public uses arguments to engage in debates about important issues. For example, environmental, health, and food production issues affect the public, which must have a legitimate voice in resolving those issues (Driver et al., 2000).

Argumentation is also associated with a social-constructivist conception of meaning making, where students learn through reflective interactions (arguments) that engage the social co-construction of knowledge (Driver et al., 2000; Newton et al., 1999). Although science educators widely endorse inquiry learning, Duschl and Osborne (2002, p. 41) argued that "teaching science as a process of inquiry without the opportunity to engage in argumentation, the construction of explanations and the evaluation of evidence is to fail to represent a core component of the nature of science or to establish a site for developing student understanding." Science as argument is to link the primary thinking activity of scientists to those of students (Kuhn, 1993).

Another reason for fostering argumentation is that it engages deeper and more mature epistemological levels of learning. By arguing the basis on which claims are made, students investigate the epistemological foundations of knowledge domains (Newton et al., 1999). At the very least, argumentation engages student thinking at the multiplicity level (some knowledge is right or wrong, but most is not yet known) on Perry's (1970) scale, and it is likely that argumentation may result in contextual relativism (students learn methods of their discipline) and possibly even commitment with relativism (choices made in the face of legitimate alternatives). Disciplinary truths must be demonstrated, not accepted on faith. Argumentation aims at the rational resolution of questions, issues, and problems (Siegal, 1995). It is not only science learning that benefits from argumentation, although science educators have focused on the roles of argumentation more extensively than other disciplines. Wineburg (2001) makes an eloquent case for the importance of argumentation in interpreting history. Argumentation is an essential way of thinking about any discipline.

Yet one more reason to foster argumentation is its effects on conceptual change. Conceptual change occurs when learners change their understanding of concepts they use and the conceptual frameworks that encompass them, reorganizing their frameworks to accommodate new perspectives. Argumentation leads to conceptual change (Asterhan & Schwarz, 2007; Baker, 1999; Nussbaum & Sinatra, 2003; Wiley & Voss, 1999). Embedding argumentation in science learning environments enhances conceptual and epistemic understanding and helps to make scientific reasoning visible (Duschl & Osborne, 2002). Similar results have been found in the humanities. For example, instructions to write an argumentative essay on a historical topic produced better conceptual understanding than instructions to write a narrative, summary, or explanation essays (Wiley & Voss, 1999). Constructing arguments engages conceptual change because of the high conceptual engagement in students (Nussbaum & Sinatra, 2003).

How Does Argumentation Affect Problem Solving?

Although problems differ (see Chapter 1), argumentation is an essential skill in learning to solve most, if not all, kinds of problems as well as a powerful method for assessing problem-solving ability for both ill-structured and well-structured problems alike (Jonassen, 2010). When students answered well-structured physics problems incorrectly and later constructed an argument for the scientifically correct answer, Nussbaum and Sinatra (2003) found that those students showed improved reasoning on the problems. When the students were retested a year later, the quality of their reasoning remained strong. This strategy engages students in refuting misconceptions. As in the case of Nussbaum and Sinatra (2003), students are refuting their own misconceptions. A number of studies have shown the effects of refuting texts that explicitly address prevalent misconceptions (Diakidoy, Kendeou, & Ioannides, 2003; Mason, Gava, & Boldrin, 2008; Salisbury-Glennon & Stevens, 1999). Refuting misconceptions by generating or reading arguments that conflict with their current knowledge can repair student misconceptions and help them to solve well-structured problems.

Argumentation pays a more obvious role in the solution of ill-structured problems. Cho and Jonassen (2003) showed that the production of coherent arguments to justify solutions and actions is a more important skill for solving ill-structured problems than for well-structured problems. Ill-structured problems are the kinds of problems that are encountered in everyday practice. They have alternative solutions to problems, vaguely defined or unclear goals and constraints, multiple solution paths, and multiple criteria for evaluating solutions so they are more difficult to solve (Jonassen, 2000c). Groups that solved ill-structured economics problems produced more extensive arguments. Because ill-structured problems do not have convergent answers or consistent solution criteria, learners must construct arguments to justify one's own assumptions, solution paths, and proposed solutions because there are no certain rules and principles to apply and there may be many possible solutions (Jonassen, 1997; Voss & Post, 1988). We have begun to establish a clear relationship between argumentation (justification) and ill-structured problem solving. I believe that argumentation provides perhaps the very best assessment of learners' abilities to solve ill-structured problems. Obviously, more empirical research is needed.

WHAT ARE THE SKILLS OF ARGUMENTATION?

What are the skills required to construct and evaluate different forms of argumentation? According to Blair and Johnson (1987), a good argument must satisfy three criteria:

1. "Is there an adequate relationship between the contents of the premises and the conclusion?" (*relevance*).
2. "Does the premise provide enough evidence for the conclusion?" (*sufficiency*).
3. "Are the premises true, probable, or reliable?" (*acceptability*).

These criteria are sufficient for judging the effectiveness of most arguments. The most comprehensive conception of the skills of argument is provided by Kuhn, who proposes thinking as a form of "formulating and weighting the arguments for and against a course of action, a point of view, or a solution to a problem" (1991, p. 2). She identifies five essential skills of argumentation:

1. Generate causal theories to support claims (*supportive theory*).
2. Offer evidence to support theories (*evidence*).
3. Generate alternative theories (*alternative theory*).
4. Envision conditions that would undermine the theories they hold (*counterarguments*).
5. Rebut alternative theories (*rebuttal*).

According to Kuhn, an argument can be considered strong if it contains these components.

Most scholars agree that providing evidence in support of claims is an important criterion for constructing arguments (Felton & Kuhn, 2001; Kuhn, 1991). However, arguers often use insufficient or inconclusive evidence to support their arguments (Walton, 1996). When arguing in support of consequences, you might ask, "How strong is the likelihood that these cited consequences will occur and what evidence supports this claim?" and "Are there other consequences of the opposite value that should be taken into account?" (Walton, 1996, pp. 76–77). If there were a formal definition of the "platonic method" of teaching, it would probably be argumentation.

How Skilled Are Students at Argumentation?

Although the skills of argumentation have been clearly identified, the abilities of students to generate or evaluate arguments is not clear. Kuhn (1991) reasoned that the skills of argument grow between childhood and adolescence (sixth to ninth grades), with college students gaining even more (Felton & Kuhn, 2001). While some researchers have shown that the ability to understand an argument emerges by age 3 (Stein & Bernas, 1999), the majority of other researchers provide counterclaims about students' abilities to understand or construct arguments. According to Reznitskya, Anderson, McNurlin, Nguyen-Jahiel, Archodidou, et al. (2001), most American students do not understand argumentative discourse. They experience difficulty:

- writing persuasive essays;
- comprehending written arguments;
- differentiating between theory and evidence;
- generating genuine evidence, alternative theories, counterarguments or rebuttals.

(Kuhn, 1991; Means & Voss, 1996)

There are serious weaknesses in the arguments of adolescents and young adults. They are unlikely to construct two-sided arguments or distinguish evidence from explanation in support of a claim (Kuhn, 1991; Kuhn, Shaw, & Felton, 1997; Voss & Means, 1991). Felton and Kuhn (2001) compared the dyadic dialogues of adolescents and young adults for five to six weeks. The teens were more focused on producing dialogue and less able to engage in strategic argumentative discourse. Nor were they able to adapt their discourse to the requirements of a particular context. The most common weaknesses in argumentation is the lack of counterargumentation. When a person is asked to generate arguments for or against his or her own position, typically more reasons are stated supporting one's own position (Stein & Bernas, 1999); however, even very young children are able to generate and think about positive and negative reasons for pursuing different courses of action or for holding sets of beliefs.

Why are students so inept at constructing arguments? Zeidler (1997) identified a number of problems with students' arguments, including selecting only evidence that supports their claims (Perkins, Farady, and Bushey (1991) refer to that tendency as "my-side bias"), a greater conviction to personal beliefs than counterevidence, overgeneralization from a single source of evidence, and making assertions that are unsupported by any evidence. Basically, students are more inclined to support their own arguments based on their own beliefs than to dig for confirming or disconfirming evidence.

Why do students argue with apparent blinders on? There appear to be three major causes:

1. Teachers lack the pedagogical skills to foster argumentation in the classroom, so there exists a lack of opportunities to practice argumentation.
2. External pressures to cover material leaving no time for skill development.
3. Learners have insufficient prior knowledge.

(von Aufschnaiter, Erduran, Osborne, & Simon, 2008; Driver et al., 2000; Newton et al., 1999)

To those causes, I would add that rhetoric was lost in curriculum reform some time ago.

WHAT KINDS OF ARGUMENTATION ARE USED?

What Are Rhetorical Arguments?

Rhetorical or persuasive arguments are conceived as a dialogue between an arguer and an audience and are the most common form of argumentation. The goal of rhetorical arguments is to persuade or convince others of a claim or proposition that the arguer believes in (Perelman & Olbrechts-Tyteca, 1969; Toulmin, 1958) without regard to positions that others hold. A rhetorical argument is successful if it gains the approval of the target audience (van Eemeren & Grootendorst, 1992). Therefore, most rhetorical arguments concentrate on developing effective persuasive argumentation techniques.

Perhaps the most prominent model of rhetorical argumentation was developed by Toulmin (1958), in which he developed a structure for argumentation, including a claim (C), data (D), a warrant (W), in addition to elements such as backing (B), qualifier (Q), and rebuttal (R) (see Figure 20.1). In the process, an arguer justifies his or her claim by linking a fact (D) to the claim (C) through a warrant (W). The qualifier (Q) conveys the degree of force from data to claim, while the rebuttal contradicts the claim (R). Toulmin rejected the existence of universal norms for evaluating arguments and contended that the validity of any argument depends on the nature of the problem. Although his model has been very influential in the field of argumentation theory, the actual application of Toulmin's model to ordinary argumentation is somewhat problematic. Although multiple-sided

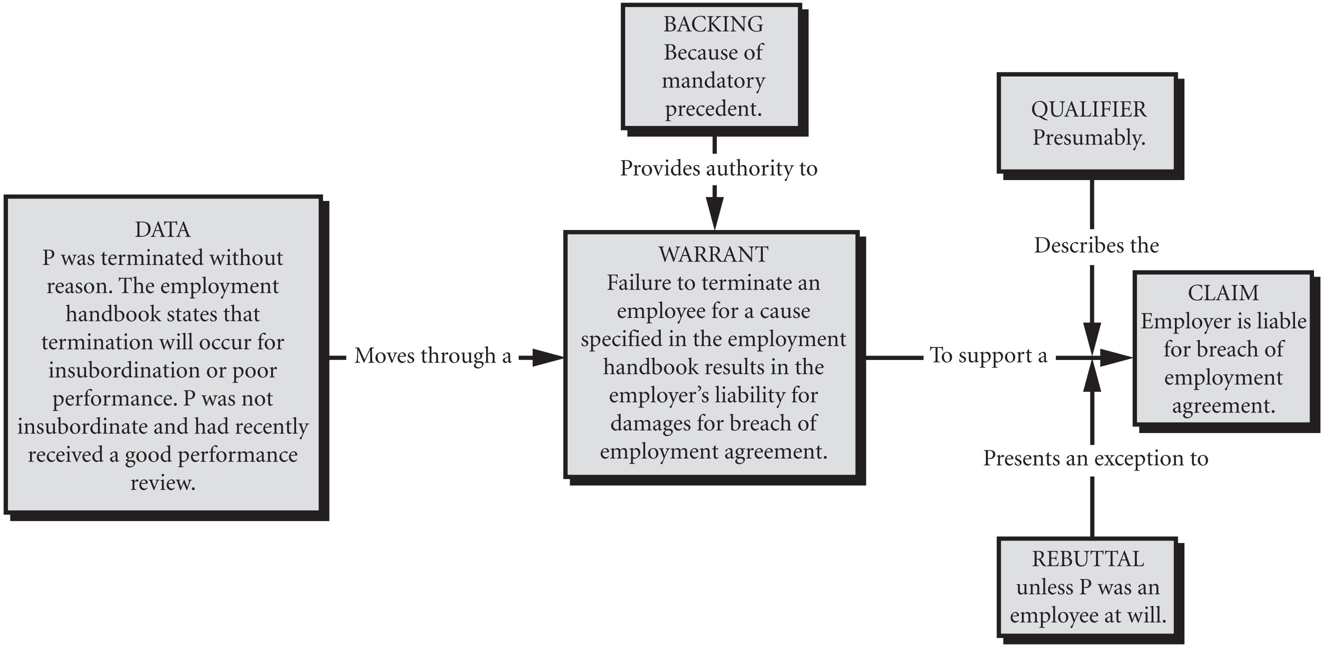


Figure 20.1 Toulmin's (1958) structure of an argument.

arguments could use Toulmin's framework for constructing arguments, his model fails to consider both sides of a controversial issue (Leitão, 2001). That is, the model depicts only proponent's side, minimizing the role of an opponent in the process of argumentation. Additionally, warrants are often implicit and therefore hard to distinguish from backing (Leitão, 2003). Toulmin's model may be useful for assessing an argument by an individual but is inapplicable for assessing an argumentation that involves two or more arguments. Although universally used to persuade others, rhetorical forms of argument are one-sided so they have limitations in educational settings (Driver et al., 2000), whether multiple perspectives should be considered.

What Are Dialectical Arguments?

Rather than a monologue between arguer and a real or imaginary audience, dialectical argumentation represents a dialogue between proponents of alternative claims during a dialogue game or a discussion. Also known as dialogical or multi-voiced arguments, the purpose of dialectical arguments is to resolve differences of opinions (Barth & Krabbe, 1982; van Eemeren & Grootendorst, 1992). That resolution may take different forms. Dialectic arguments may be adversarial, where the goal is to convince opponents of the superiority of one's claim. They may also seek a compromise between multiple claims. Dialectic arguments may take place within individuals (e. g., making a decision) or within social groups (Driver et al., 2000).

Because dialectic arguments are considered more applicable to problem solving than rhetorical arguments, I briefly describe two prominent models of dialectical argumentation, pragma-dialectics (van Eemeren & Grootendorst, 1992) and argumentation schemes for presumptive reasoning (Walton, 1996), which provide useful insights into dialectical argumentation.

Pragma-dialectics (van Eemeren & Grootendorst, 1992; van Eemeren, Grootendorst, & Henkemans, 1996) views argumentation as a means of resolving differences of opinions in critical discussions and suggests a formal model for conducting those discussions. Critical discussions have four essential stages:

1. confrontation stage;
2. opening stage;
3. argumentation stage;
4. concluding stage.

(van Eemeren & Grootendorst, 1992; van Eemeren et al., 1996)

During the confrontation stage, people present their different claims. If there are no differing views, then there is no argument. During the opening stage, people accept their roles and a set of rules for conducting the argument. In the argumentation stage, people defend their claims and challenge others. In the concluding stage, participants decide who wins and loses. Pragma-dialectics provides a useful model for conducting classroom or online discussions.

A more useful model of argumentation for educational purposes is Walton's (1996) concept of presumptive arguments. Walton claims that argumentation is a goal-directed and interactive dialogue in which participants reason together to advance arguments by proving or disproving presumptions. In arguments based on presumptions, the reasoning is tentative and open to challenge (Walton, 1992). In presumptive arguments, the burden of proof is shifted to the other party in a dialogue (Walton, 1996). Therefore, in dialectical argumentation, counterarguments are just as important as the original argument. Walton (1996) identified twenty-five presumptive argumentation schemes and provided a matching set of critical questions that should be asked by respondents. These schemes provide specific models for structuring classroom and online discussions. For purposes of supporting most kinds of problem solving, dialectical arguments supporting alternative interpretation or solutions will be more effective than rhetorical arguments, with an emphasis on generating and rebutting counterarguments.

HOW IS ARGUMENTATION ENGAGED AND SUPPORTED?

If students are not very capable of constructing cogent arguments, how can we support the development of the skills of argumentation? There exist numerous methods of argument-skill development for fostering argumentative discourse (Felton & Kuhn, 2001; Kuhn et al., 1997). In this section, I describe the most common methods for engaging and supporting argumentation among students along with research evidence in support of those methods. These methods may be applied to classroom instruction or open-ended learning environments to enhance conceptual understanding and problem solving.

Before describing methods for engaging and supporting argumentation in PSLEs, it is important to point out the importance of the problem-solving outcomes. Argumentation will be more effective when student are engaged in problem-based learning, especially with ill-structured problems, where alternative interpretations and solutions necessitate argumentation. Students who are required to memorize information have little reason to engage in argumentation. Problem-based learning environments typically present alterative claims or solutions that learners must resolve through argumentation. The following methods will be more effective if students have a legitimate reason to argue.

How Can Directions Engage Argumentation?

The most obvious method for engaging argumentation is to provide a set of directions for constructing arguments. The purpose of directions is to engage specific forms of argumentation among students. Among the most common directions is that to produce counterarguments. Counterargumentation is a defining attribute of good argumentation (Andriessen, Baker & Suthers, 2003; Voss, Perkins, & Siegel, 1991) and a standard for assessing arguments (Kuhn, 1991). Counterargumentation is important because reasoning is fundamentally dialogical (Anderson, Nguyen-Jahiel, McNurlin, Archodidou, Kim, Reznitskaya, et al., 2001). However, it is hard for children to generate counterarguments because of self-centering and a lack of knowledge to support opposing points of view (Leitão, 2001, 2003). Nussbaum and Kardash (2005) conducted two experiments where they provided directions for different kinds of student essays.

> **Persuasion Condition**: Please write an essay expressing your opinion on the following question, "Does watching TV cause children to become more violent?" Provide as many reasons as you can to justify your position, and try to provide evidence that supports your reasons.
>
> **Counterargue/Rebut Condition**: Please write an essay expressing your opinion on the following question, "Does watching TV cause children to become more violent?" Provide as many reasons as you can to justify your position, and try to provide evidence that supports your reasons. Then discuss two or three reasons why others might disagree with you, and why those reasons are wrong.

As expected, Nussbaum and Kardash (2005) found that persuasion instructions reduced the number of counterarguments generated by students. This finding was consistent with a study by Stein and Bernas (1999) that showed that arguers better support their own position than they do opponents' positions because they perceive more benefits accruing from their own position vs. another's, an example of my-side bias. The students in the Nussbaum and Kardash study actually believed that identifying counterarguments would make their own arguments less persuasive.

In the second experiment, they focused on the purpose of the argument construction: to persuade or not.

> **Persuasion Condition**: Imagine that a campaign is being waged in Congress to consider tougher laws on TV violence. The fundamental issue is, "Does watching TV causes children to become more violent?" Write a letter trying to persuade and convince your Congressional representative how he or she should vote on this issue, for or against.

They found that the instructions to persuade had a negative effect on the holistic quality of essays as well as the number of reasons supporting their counterclaims. However, when provided a text that outlined numerous arguments on both sides of the issue, the contrasting text counteracted the negative effects of persuasion instructions. Research has shown that directions to argue in different ways do affect students' argumentative performance.

How Do We Prompt Argumentation with Questions?

A number of researchers have explored how to scaffold argumentation in learners by asking questions. Kuhn (1991) provided specific questions to students that are based upon her skills of argument (described before). She focused on asking students about controversial issues, using questions such as:

1. What do you think is the cause of school failure?
2. How would you prove that this is the cause?
3. What might somebody else, who does not agree with you, think is the cause of school failure?
4. What could you tell her/him to show he or she is wrong?
5. What might somebody else say to show that your opinion about the cause of school failure is wrong?
6. What could you tell her/him to show he or she is wrong?

In another set of studies, Nussbaum et al. examined a variety of strategies to prompt better arguments, including:

- the refutation strategy;
- the synthesizing strategy;
- the weighing strategy.

(Nussbaum & Schraw, 2007)

In the refutation strategy, an explicitly adversarial strategy, students learn to recognize alternative solutions and to rebut other arguments ("What solution might someone else recommend, and how would you respond to their reasons?"). In the synthesizing strategy, students try to develop a compromise position that combines merits of both sides ("Is there a compromise or creative solution?"). Smith, Johnson, and Johnson (1981) found that controversy promotes higher achievement and retention, greater understanding, and higher motivation than concurrence strategies. In the weighing strategy, students must learn to evaluate alternative arguments and to support the stronger argument based on the weight of evidence on that side of the issue ("Which side is stronger and why?").

In Chapter 18, I described a questions that addresses causal relationships (Osborne, Enduran, & Simon, 2004): "When you exercise your skin gets redder especially in your face." Which statement explains best the observation.

1. Your blood pressure increase increases causing more blood to the surface of your skin.
2. Your blood is pumped to the surface for gaseous exchange to occur.
3. Your blood carries more oxygen and therefore is a deeper color.
4. Your blood gets closer to the surface for excess heat to be lost.

Requiring students to explain why assesses whether they really understood the lesson and engages them in argumentation. Students then have access to evidence statements that enable them to reconsider their claims and present argument with more justification.

1. Blood pressure in the capillaries is likely to be less as the volume has increased so that more blood can pass through them.
2. Gaseous exchange is when carbon dioxide diffuses out of the blood and oxygen enters the blood. This takes place in the lungs.
3. The more oxygen carried by the red blood cells deepens the color. This would be difficult to see. However, a quick test for anemia is to stretch your hand and see if you can see red through the lines.
4. Blood vessels relax allowing more blood to the surface so that heat can be lost to maintain your internal body temperature.

Jonassen, Cho, Kwon, Henry, Easter, Shen, et al. (2009) conducted research studies that engaged students in argumentation about engineering ethical dilemmas. They evaluated treatment that compared evaluating arguments with constructing arguments. Participants in the evaluate treatment were asked to evaluate two alternative solutions while interacting with the case evidence. Each participant answered a series of questions:

- Which solution is better, solution 1 or solution 2?
- Whose perspective(s) support(s) your selection?
- Which theoretical approach(es) support(s) your selection?
- Which ethical codes support your selection?
- How might someone supporting the other solution disagree with your preferred solution?

In the construct treatment, participants were asked to construct their own solution to ethics cases. Participants were asked:

- What should you, as the engineer, do? What is your solution to this ethical problem?
- Whose perspective(s) support(s) this solution?
- Which theoretical approach(es) support(s) your solution?
- Which ethical codes support your solution?
- What might someone else do? What alternative solution might someone recommend?
- What reasons would someone provide to support this solution?

Students who evaluated alternative arguments better supported their arguments on an immediate transfer task. In doing so, they provided more elaborate discussions and justifications for their solutions to ethics problems. While the evaluate treatment supplanted argumentation skills among lower-achieving students, the construct and control treatments did not enhance students' argumentation skills. Consistent with other research (Felton & Kuhn, 2001; Kuhn, 1991; Kuhn et al., 1997; Stein & Bernas, 1999; Voss & Means, 1991), students in this study failed to adequately consider and support counterclaims, providing more elaborate support for their own solutions. Follow-up studies will focus on supporting more elaborate counterarguments.

An alternative form of questions can be found in the use of note starters. Note starters consist of a menu of phrases from which students begin the first sentence of discussion note in an online discussion board. For example, Nussbaum, Hartley, Sinatra, Reynolds, and Bendixen (2004) used note starters and elaborated cases to encourage counter-argumentation. The note starters encouraged students to consider other points of view. Preclassifying conversational requirements provides a set of canonical relations that constrain the nature of verbal interactions among conversants. These constraints form the links or relations between the ideas that conversants produce. In a study with preservice teachers solving diagnosis–solution (classroom-management) problems, Oh and Jonassen (2007) used the online discussion tool, FLE3 (Future Learning Environment 3) to mediate students' argument

What is the cause?

fleadmin

One possible cause is that

18 29 2004-02-0

The problem is caused by

Show bodies of all notes

- (Problem_Identification) Problem is / fleadmin / 2004-02-08
    - (Hypothesize_Cause) One possible cause is that / fleadmin / 2004-02-08
        - (Solution_Generation) I suggest that / fleadmin / 2004-02-08
        - (Verification) I agree / fleadmin / 2004-02-08
            - (Rebuttal) I don't think so / fleadmin / 2004-02-08
            - (Evidence_Research) Research shows that the problem is / demo / Yesterday
        - (Elaboration) Your explanation is not clear! / fleadmin / 2004-02-08
            - (Evidence_Beliefs) I believe that / fleadmin / 2004-02-08
        - (Verification) I agree with what you said because / demo / Yesterday
        - (Elaboration) I can't understand your points. / demo / Yesterday

Figure 20.2 Notestarters as organizer for online arguments.

construction. FLE3 permits the teacher or designer to build in constraints and then assign note starters to help the student write their constrained responses. Figure 20.2 illustrates ten different kinds of constrained notes that can be created to support an argument along with the note starters. After selecting a note starter, participants enter their text, images, URLs, or other supporting evidence. Oh and Jonassen (2007) found that the discussion group using note starters generated more evidence notes and that individuals who believe in simple knowledge and solutions to ill structured problems are less inclined to explore solution alternatives. The research on constraining discussions is quite new. Although these environments promise enhanced reasoning, more research is needed to confirm the effectiveness of these tools.

How Can Graphical Argumentation Systems Help?

A number of tools and environments are becoming available for helping learners to visualize arguments in order to improve their construction (Kirschner, Buckingham-Shum, & Carr, 2003). Visualizing argumentation enables students and faculty to see the structure of the argument, thus facilitating its more rigorous construction and subsequent communication (Buckingham Shum, MacLean, Bellotti, & Hammond, 1997). It also helps learners visualize and identify "the important ideas in a debate as concrete objects that can be pointed to, linked to other objects, and discussed" (Suthers & Jones, 1997, p. 1).

The simplest form of graphic support is a graphic organizer. Nussbaum and Schraw (2007) developed a graphic organizer for plan-

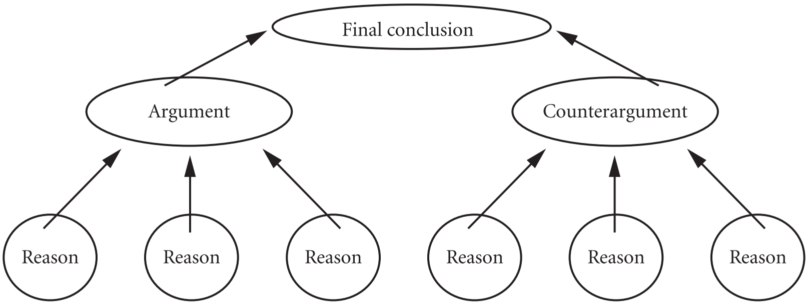


Figure 20.3 Graphic organizer for developing arguments, counterarguments, and a final conclusion on an issue (Nussbaum & Schraw, 2007).

ning arguments and counterarguments, supporting reasons, and a final conclusion while preparing to write an argumentative essay (see Figure 20.3). Participants fill in the circles with their claims and supporting reasons. The purpose of this oval was to help students to weigh the relative strengths of the arguments and counterarguments while negotiating a final conclusion as well as developing rebuttals. They found that using the graphic organizer resulted in more refutations of counterarguments, one of the major weaknesses in argumentation. This Vee diagram is especially useful when students are considering alternate solutions to an ill-structured problem. Helping students to construct a powerful dialectical argument provides better solutions.

HOW SHOULD ARGUMENTATION BE IMPLEMENTED IN PSLEs?

Argumentation is one of the most important cognitive processes engaged in solving most kinds of problems (Jonassen, 2010). Arguments also frequently have affective or emotional aspects; however, the more emotion that is embedded in arguments, the more the arguments degrades, at least cognitively. Therefore, I address only the cognitive dimensions of argumentation. In most PSLEs, problem solving may be engaged by including some form of argumentation in the environment. The purposes of those argumentation activities are to support better problem solving or to assess students' understanding of domain content and problem-solving skills.

Argumentation may be used primarily to justify problem interpretations and problem solutions. Following the presentation of a case as problem to solve (see Chapter 8), students will use cases as analogues (Chapter 11), cases as prior experiences (Chapter 12) or cases as alternative perspectives (Chapter 13) to characterize what kind of problem is being solved and what important questions or issues need to be addressed. All of these are open to interpretation and therefore subject to argumentation. So, you may want to require students to construct arguments in support of their problem interpretation.

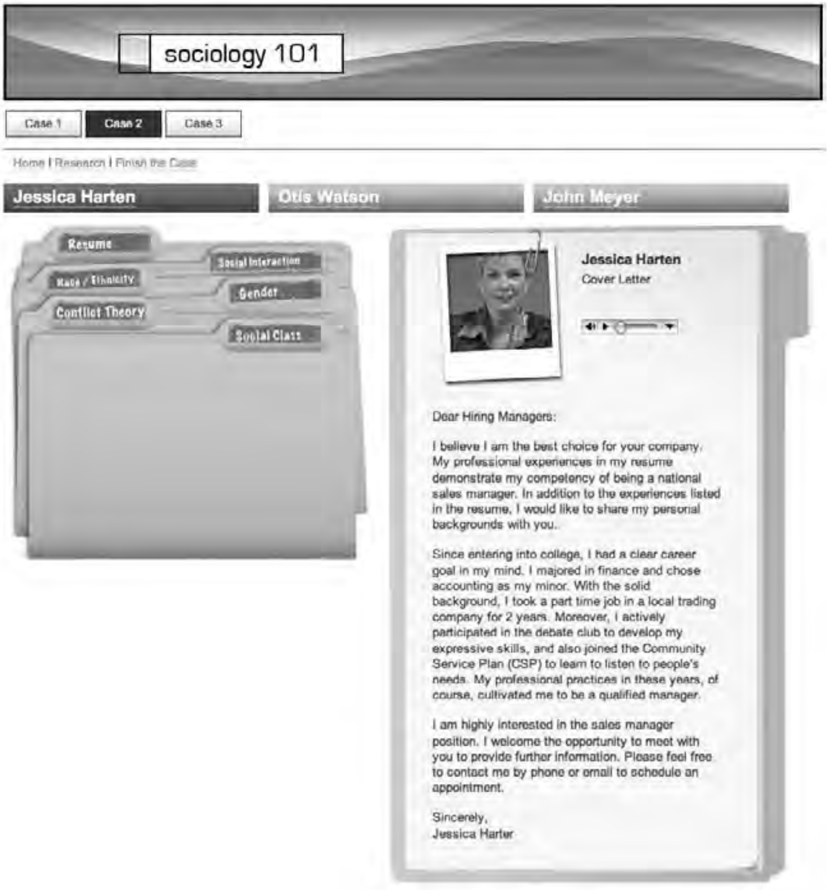
Arguments should also be used to help students to justify alternative solutions to the problem. Clearly, dialectic forms of argumentation are appropriate (see Figure 20.3 for a graphic depicting the structure of such an argument). Individual students or groups of students could make a claim about the best solution and justify it in terms of warrants or case evidence which they garner from the case as presented or from outside research. For example, we are currently conducting research on argumentation in an introductory sociology class. Similar to the engineering ethics, we are using argumentation as the primary method for assessing students' abilities to apply sociological theories. In a series of cases (evaluating applications of potential tenants, evaluating job applicants, and evaluating applicants for special admission to university), students examine a variety of applicants based on their credentials, race/ethnicity, gender, social class, and social interaction and conflict theories to understand how they affect everyday sociological decisions (see Figure 20.4). In addition to a video interview, selecting the folders presents the applicants' cases from those perspectives. In this case, students were required to answer the following questions:

- If you were the CEO of this company, which candidate would you choose?
- What relevant sociological concepts and facts support your choice?
- What sociological concepts and facts might one of the other Vice Presidents cite to support one of the other candidates?
- What sociological concepts and facts would you use to promote your choice over the other Vice President's arguments?

We regard these prompts and the format of the information in each folder as argument scaffolds, helping students to construct a coherent argument. These directions are specific to the problem case and would not apply to other problems.

HOW DO WE ASSESS ARGUMENTS?

If you require your learners to construct arguments to support problem interpretation or solutions, then it is necessary to assess the quality of them. The most common method for assessing argumentation is protocol analysis of student essays or responses to questions that



Jessica Harten
Cover Letter

Dear Hiring Managers:

I believe I am the best choice for your company. My professional experiences in my resume demonstrate my competency of being a national sales manager. In addition to the experiences listed in the resume, I would like to share my personal backgrounds with you.

Since entering into college, I had a clear career goal in my mind. I majored in finance and chose accounting as my minor. With the solid background, I took a part time job in a local trading company for 2 years. Moreover, I actively participated in the debate club to develop my expressive skills, and also joined the Community Service Plan (CSP) to learn to listen to people's needs. My professional practices in these years, of course, cultivated me to be a qualified manager.

I am highly interested in the sales manager position. I welcome the opportunity to meet with you to provide further information. Please feel free to contact me by phone or email to schedule an appointment.

Sincerely,
Jessica Harter

Figure 20.4 Sociology environment engaging argumentation.

are gathered in the classroom or in online discussion forums. Whether your arguments are in the form of essays or discussion-board comments, it is necessary to identify idea units within the essays or messages. Idea units are the distinct ideas that are represented in the essays or student comments. Begin looking for idea units by examining sentences. A sentence may contain more than one idea unit, and it is likely that a learner may require two or more sentences to convey a claim, reason to support their claim, or a counterargument.

Having identified idea units, the next step is to classify those units with a coding scheme. Nussbaum and Kardash (2005) asked students to write essays on whether TV causes violence. They first examined the essays for the final claim of the author. Next, they looked for the reasons

Table 20.1
Coding scheme for analyzing student responses (Jonassen, Cho, et al., 2009)

Coding Category	**Description**	**Example**
Solution	An opinion to solve a given dilemma problem	To solve this problem I would make sure the managers know the implications of the old software and plead to get the extension in order to make the software up to date.
Solution Supporting Perspective	A perspective of a stakeholder that supports the solution	Customers would love to know that the company is following new guidelines.
Solution Supporting Theory	A theory (utilitarian, rights and duty, virtue) that supports the solution	The Rights & Duty theoretical approach tells me that the public of the city have the rights to live in a safe city and to work.
Solution Supporting Canon	A canon that supports the solution	First and foremost it is imperitave to follow the first ethical canon because a flaw or error in the control systems for air could severely put in danger the health of the employees at the power plant, the environment, wildlife, and local commuinities of people.
Counterclaim	A claim that refutes the solution	There will be some sacrifices in order to add the newly design software.
Counterclaim Supporting Perspective	A perspective of a stakeholder that supports the counterclaim	The sacrifices would be the costumers will have to wait patiently in order to recieve thier product. Some of them will start to get mad and irritated.
Counterclaim Supporting Theory	A theory (utilitarian, rights and duty, virtue) that supports the counterclaim	By the Utilitarian approach we can see that the company and the client profit in the short term with keeping the software as is.
Counterclaim Supporting Canon	A canon that supports the counterclaim	If this proves too costly, than selling the product as is, is not necessarily unethical because it meets current standards, and those standards had to be comparable at one point.

that students provided and classified them as primary claims. Third, they identified reasons that students provided in support of their primary claims, and next, they identified any counterclaims generated by students. Finally, they examined student essays for rebuttals. These categories were used as a coding scheme for analyzing student essays.

In the Jonassen, Cho, et al. (2009) study, we used a similar scale (see Table 20.1) to analyze the student responses to transfer cases. In our analysis, we specified the types of supporting reasons (perspectives, theories, or ethical canons) that students provided to support their solutions to the ethical dilemmas. In our study, students who evaluated alternative arguments better supported their arguments on the immediate transfer task. They provided more elaborate discussions and justifications for their solutions to ethics problems. When support categories (perspectives, theories, and canons) were combined, distinct differences among treatments were shown.

Argumentation can also be assessed using carefully crafted objective assessment questions, even in objective form. Earlier in the chapter, I described questions used by Osborn et al. (2004) in their research, where they asked a multiple-choice question requiring students to explain why one's skin gets redder when one exercises. That follow-up question called for an explanation of the reasons for a phenomenon, which is an implicit form of argumentation. Such questions are useful in assessing individual argumentation skills.

When the goal is to assess the effects of collaborative argumentation, different assessment methods are necessary. The first step is to describe the structure of collaborative argumentation in social settings (Keefer, Zeitz, & Resnick, 2000). What are the features of collaborative reasoning (i.e. premises, conclusions, challenge or answer to challenge, and concession). Note that these codes address the social interaction processes in argumentation. Next, each person's message is categorized according to its function (e.g., a challenge) in relation to a previous argument. Finally, each category was placed within the overall collaborative reasoning structure.

In addition to assessing the quality of student arguments, another reason to assess students' arguments is their predictive validity. A little bit of research has confirmed that argumentation provides the important evidence of problem-solving ability, especially for ill-structured problems (Cho & Jonassen, 2003; Shin, Jonassen, & McGee, 2003). Because ill-structured problems possess multiple solutions and solution criteria, supporting problem solutions with arguments is perhaps the best form of assessment possible. More research is needed to establish the connection between argumentation and problem solving.

21

METACOGNITIVE REGULATION OF PROBLEM SOLVING

WHAT IS METACOGNITION?

Based on Flavell's initial conception of metamemory, Brown (1978, 1987) and Flavell (1976, 1979, 1987) contributed most to a theory of metacognition. Although the original research focused on helping children become more aware of the learning strategies they use while studying, metacognition has become an umbrella term for metamemory, metacomprehension, self-monitoring, metacognitive monitoring, self-directed learning, and self-regulated learning.

Flavell (1976, 1979) distinguished two characteristics of metacognition: knowledge of cognition and regulation of cognition (see Figure 21.1). Knowledge of cognition includes knowledge of task, strategy, and personal variables. That is, metacognitive knowledge includes knowledge of the skills required by different tasks, strategic knowledge (knowledge of alternative learning strategies and when to use them) and self-knowledge (knowledge of one's abilities and the abilities of others) (Flavell, 1987). Metacognitive knowledge also includes knowledge about cognition in general as well as knowledge of one's own cognition. Although the knowledge of cognition factor of metacognition is stable, it is often difficult to distinguish between what is cognitive and what is metacognitive (Brown, 1987). Other research has shown that metacognitive knowledge is related to crystallized intelligence (Rozencwajg, 2003), a basic form of intelligence associated with the ability to remember and use acquired knowledge.

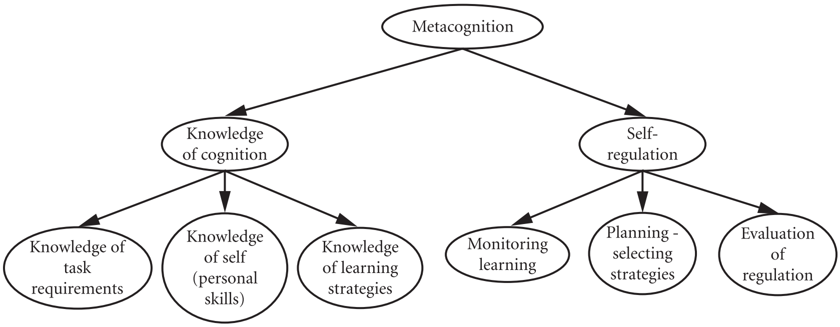


Figure 21.1 Conceptual components of metacognition.

Regulation of cognition includes the ability to monitor one's comprehension and to control one's learning activities. For example, when a student realizes that "I did not understand the concept of entropy," the student is monitoring their comprehension. When they decide to employ another strategy to enhance understanding (e.g., reading another source, consulting graphs), they are controlling their learning. The self-regulation factor of metacognition describes activities that regulate and oversee learning such as planning (predicting outcomes, scheduling strategies) and problem-monitoring activities (monitoring, testing, revising and rescheduling during learning). Self-regulation also involves evaluation (appraising the effectiveness of regulation) (Schraw & Moshman, 1995). These skills are referred to elsewhere as self-regulated learning (Pintrich, 1999; Zimmerman & Schunk, 1989). The ability to monitor and regulate learning processes is based on metacognitive experiences (Flavell, 1987) and is more closely associated with fluid intelligence (Rozencwajg, 2003), the form of intelligence associated with problem solving and reasoning beyond acquired knowledge.

Although introduced as separate metacognitive entities, knowledge of cognition and regulation of cognition are integrated. Knowledge of cognition, according to Flavell (1979), is essential for planning, monitoring, and regulating learning processes. These reciprocal entities been embraced and elaborated by others (e.g., Bransford, Brown, & Cocking, 1999; Pintrich, 2002) and were validated by Schraw and Dennison (1994) in the development of the Metacognitive Awareness Inventory (MAI) (described later).

Following the lead of Brown and Flavell, numerous researchers have explored the role of metacognition among diverse audiences focused on different learning tasks. In their revision of Bloom's Taxonomy of Educational Objectives, Anderson, Krathwohl, Airasian, Cruikshank, Mayer, Pintrich, et al., (2001) accommodated metacognitive knowledge to the knowledge dimension of the taxonomy. Included in metacognitive knowledge are strategic knowledge (knowledge of different learning strategies), knowledge about different cognitive tasks (including contextual and conditional knowledge about the nature of tasks to be performed), and self-knowledge (knowledge of one's own goals and abilities). In their conception, the executive control processes were not added to the cognitive process dimension. Perhaps the broadest conception of cognitive processing was provided by Kitchner (1983). At the first level, learners engage in *cognitive* tasks (memorizing, computing, reading, problem solving). At the second level, learners engage in metacognitive reasoning, including knowledge about cognitive tasks and strategies to improve performance. At the third level, epistemic cognition, learners develop epistemological perspectives about the limits and certainty of knowing as well as skills for developing alternative solution to different kinds of problems.

HOW IS METACOGNITION ASSESSED?

Metacognitive awareness has been assessed in a variety of ways. Early research focused on inferring metacognitive processes from think-aloud protocols that students generated while reading or working through problems. Artz & Armour-Thomas, 1992; Schoenfeld, 1983). In these episodes, learners were instructed to verbalize their thinking while performing learning tasks. Those protocols were then analyzed using various coding schemes. For example, Artz and Armour-Thomas (1992) analyzed problem-solving episodes for their metacognitive processes, including understanding the problem, analyzing, exploring, planning, implementing, and verifying solutions. Some researchers employed participant observation of learners engaged in similar tasks.

The most commonly used method for assessing metacognitive awareness has been the self-report instrument. Several researchers have developed survey instruments to assess metacognitive awareness. Swanson (1993) constructed a survey for assessing problem-solving processes in learning-disabled students. Students responded to questions, such as:

- **Good reader question**: The other day I talked to a boy (or girl) who was really good at solving problems. Then I asked him (or her) if he (or she) was a good reader. What do you think he (or she) said? Why?
- **Piano question**: Jim can play the piano, draw pictures, and figure out his math problems better than anyone else in the class. Do you think he's the smartest person in the class? Why?

- **Liar question**: Ann was lost in a forest, and she came to a town in which there were two kinds of people, "truth tellers" and "liars." Truth tellers always tell the truth and liars always lie. The first person Ann talks to gives her directions to get home. The second person she talks to gives her different directions. Does Ann have a problem to solve? Why?

The validity of this instrument has been questioned (Sigler & Tallent-Runnels, 2006).

The most commonly used self-report instrument has been the MAI (Schraw & Dennison, 1994). Believing that metacognitive awareness enables learners to plan, sequence, and monitor their learning, they factor analyzed a fifty-two-item Likert-scale instrument. After unrestricted factor analysis produced unreliable results, they forced a two-factor solution, consisting of a knowledge of cognition (declarative, procedural, and conditional knowledge) factor and a regulation of cognition factor, empirically supporting Flavell's definition of metacognition. Sample questions in each factor include:

Knowledge of Cognition Factor
- I understand my intellectual strengths and weaknesses.
- I can motivate myself to learn when I need to.
- I am a good judge of how well I understand something.
- I focus on the meaning and significance of new information.
- I learn more when I am interested in the topic.

Regulation of Cognition Factor
- I set specific goals before I begin a task.
- I ask myself questions about the material before I begin.
- I ask myself how well I accomplish my goals once I'm finished.
- I ask myself if I learned as much as I could have once I finish a task.
- I ask myself if I have considered all options after I solve a problem.

The MAI has been validated by comparing scores on the MAI to scores on related instruments. For example, Sperling, Howard, and Staley (2004) correlated MAI scores with scores on the Learning Strategies Survey (LSS; Kardash & Amlund, 1991) and the Motivated Strategies for Learning Questionnaire (MSLQ; Pintrich, Smith, Garcia, & McKeachie, 1991), as well as accuracy ratings of test performance. They found strong correlations between the MAI and LSS instruments. Both the knowledge of cognition and regulation of cognition factors consistently correlated with LSS. They also found strong correlations between the

MAI and Metacognitive Self-Regulation and Time and Study Environments Management scales of the MSLQ. Their results support construct validity of the MAI. In another study, the knowledge of cognition factor correlated with MSLQ, predictions of test performance, and test scores while the regulation of cognition correlated with scales on MSLQ. Based on this support, the MAI has been used extensively in research studies to assess metacognitive awareness.

Howard, McGee, Shia, and Hong (2000) developed the Inventory of Self-Regulation, including thirty-seven Likert-scale items. Their goal was to identify metacognitive skills that were specific to problem solving. They discovered five metacognitive and self-regulatory factors that were relevant to problem solving, including:

Knowledge of Cognition (understanding cognitive abilities and how they learn best)

- I use different ways to memorize things.
- When it comes to learning, I know how I learn best.

Objectivity (standing outside oneself)

- I think about how well I am learning when I work a difficult problem.
- I ask myself how well I am doing when I learn something new.

Problem Representation (problem definition)

- I try to understand what the problem is asking me.
- I read the problem over and over until I understand it.

Subtask Monitoring (monitoring subtasks and strategies used)

- I try to break down the problem to just the necessary information.
- I think about what information I need to solve this problem.

Evaluation (evaluate if problem solved correctly)

- I double check to make sure I did it right.
- I look back on the problem to see if my answer makes sense.

The MAI and most other instruments assess metacognition as a trait variable, that is, how commonly and consistently students engaged in metacognitive behaviors across tasks. Assuming that metacognition may be task-specific, O'Neil and Abedi (1996) validated an instrument that assessed metacognition as a state variable, that is, processing specific to a task or state. The task they examined was test taking. Twelfth graders completed the instrument just after taking a math test. They validated four state factors with sample questions, including:

1. Awareness
- I was aware of my own thinking.
- I was aware of my ongoing thinking processes.

2. Cognitive strategy
- I attempted to discover the main ideas in the test questions.
- I selected and organized relevant information to solve the test questions.

3. Planning
- I tried to determine what the test required.
- I tried to understand the test questions before I attempted to solve them.

4. Self-checking
- I checked my work while I was doing it.
- I checked my errors as I progressed through the test.

Armour-Thomas and Haynes (1988) developed a similar instrument, Student Thinking About Problems Solving Scale (STAPSS), for assessing metacognitive processes associated with problem solving. They isolated six separate factors:

1. planning (what information is needed, steps to be taken);
2. organizing (available information);
3. accommodating (adjusting strategy based on information);
4. evaluating (assess understanding of problem, plans for and ability to solve problem);
5. strategizing (planning, monitoring, and evaluation);
6. recapitulating (reflection on process).

Their instrument was found to have modest predictive validity related to problem solving.

Other researchers have assessed student perceptions of how successfully they have completed certain tasks. For example, Metcalfe (1986) developed a simple prompt called "feeling of warmth." Based on the children's game of hide-and-seek, prompts are provided during task performance asking students if they are getting warmer in their search for a solution. More capable problem solvers more accurately estimated their closeness to solution (feeling of warmth) and had greater knowledge about cognitive strategies and when to apply them, as well as rating their metacognitive awareness higher using feeling of warmth (Jausevec, 1994).

HOW IMPORTANT IS METACOGNITION TO PROBLEM SOLVING?

Historically, most of the research on metacognition has focused on reading comprehension strategies to enhance normal classroom studying. However, a growing body of research has also examined metacognitive skills in support of problem solving. The difference between good and poor problem solvers is the ability to think about one's problem solving activities (Davidson & Sternberg, 1998). Regardless of aptitude, higher-metacognitive children solve problems better and more quickly than the lower-metacognitive children. Metacognitively skilled learners think about problems differently. For example, Swanson (1990) found that higher-metacognitive-ability groups were more likely to rely on hypothetico-deductive reasoning (if-then propositions) and evaluation (check the adequacy of a hypothesis) strategies than lower-metacognitive learners. That is, high metacognitive skills can compensate for overall ability by providing knowledge about cognition.

Several researchers have examined the general metacognitive processes required to solve of problems. Metacognition helps problem solvers to recognize that there is a problem to be solve, define the problem, and understand how to reach a solution (Davidson, Deuser, & Sternberg, 1994). They articulated the metacognitive processes used during problem solving:

1. identifying and defining problem (determining what kind of problem it is);
2. mentally representing problem (develop mental model of problem);
3. planning solution procedure (especially when problem is novel and complex, weighing costs and benefits);
4. evaluating performance (evaluating mental representation of problem).

While developing and validating a taxonomy of metacognitive activities engaged in problems based on think aloud protocols, Meijer, Veenman, and Hout-Walters (2006) identified numerous metacognitive strategies used in problem solving, including:

- establishing task demands, formulating action plans;
- executing action plan;
- finding similarities among problems (analogical reasoning, see Chapters 11 and 16);
- noticing inconsistencies and confusion;

- identifying restrictions to solution;
- transferring from one representation to another;
- activating prior knowledge;
- assessing difficulty of problem.

A large body of the research on metacognition and problem solving has been conducted with mathematical problems. Of all the conceptions of metacognition, self-regulation or monitoring and control is most important to mathematical problem solving (Schoenfeld, 1992). Math novices typically read a problem, choose an approach, and then persist in that approach, whereas math-faculty members spend more than half of their time trying to make sense of the problem (analyzing and planning). After metacognitive instruction, students try a solution, recognize that it is not working, and move on to another solution. There is a dynamic interaction between mathematical concepts and processes (including metacognitive ones) used to solve problems using those concepts (Lester, Garofalo, & Kroll, 1989). That is, control processes and awareness of cognitive processes develop concurrently with an understanding of math concepts. The research on metacognition in math problem solving has focused in the skills required to solve very well-structured problems, such as algorithms and story problems.

Unlike research on math problem solving, a little bit of research has examined the role of metacognition in solving more ill-structured kinds of problems. Metacognition has been shown to be important for the solution of more open-ended (creative) problems as well as well-structured problems (Jausevec, 1994). Students who had high levels of state metacognition were more successful at solving analytical problems from the Graduate Record Examination than students low in trait metacognition (Coutinho, Wiemer-Hastings, Skowronski, & Britt, 2005). However, students who scored high in trait metacognition did not seek out problem explanations any more often than students low in trait metacognition, so they did not perform any better on problem-solving tasks. A great deal more research is needed to identify the metacognitive skills required for solving different kinds of problems.

A couple of research teams have examined the role of metacognition in decision making (see Chapter 3). Although both knowledge and regulation of cognition are related to decision-making performance, regulation of cognition had greater effect on decision making than knowledge of cognition (Batha & Carroll, 2007). They showed that metacognitive strategy instruction can improve decision making. Gott, Lajoie, and Lesgold (1991) found that along with understanding the system (a robust device model), learning to troubleshoot also requires executive control processes to guide learners through very complex problem spaces. Again, more research is needed to articulate the metacognitive skills that are supportive of decision making.

HOW DO WE SUPPORT METACOGNITION DURING PROBLEM SOLVING?

While there is considerable diversity regarding the meaning of metacognition, there is even more diversity of opinion regarding how to support metacognitive processing during learning. Metacognitive skills can be learned from explicit training or through coaching (Schoenfeld, 1992). There are two primary approaches to metacognitive training: strategy training and creation of a supportive social environment (Lin, 2001). Training focuses on two kinds of content: knowledge about specific domain and self-as-learner (self-knowledge). Strategies that may be trained include error detecting, allocation of attention and effort, elaborating, self-questioning, self explanations, constructing visual representations, activating prior knowledge, rereading difficult text sections, and revising. According to Lin (2001), instructional approaches to domain-specific strategies include modeling metacognitive strategies, prompting actions, and reflecting on self-as-learner. A review of all of these approaches is beyond the scope of this book.

The most common method for supporting metacognition while learning to solve problems has been the insertion of question prompts during learning, a form of coaching. Inserted questions may well be the most effective metacognitive strategy in problem-solving learning environments. For example, Hoffman and Spatariu (2008) suggest using prompts, such as:

- Have you solved similar problems before?
- What strategy can you use to solve these problems?
- What steps are you taking to solve the problem?
- Can your answer be checked for accuracy?
- Are you sure that your answers are correct?
- Can the problem be solved in steps?
- What strategy are you using to solve the problems?
- Is there a faster method to solve the problem?
- Are these problems similar to addition in any way?
- What is the best method to solve the problem?

According to their research, these prompts improved both problem-solving accuracy and problem-solving efficiency, suggesting that under increasingly complex problems, metacognitive prompts induce greater cognitive awareness and the utilization of effective problem-solving strategies.

While solving case studies, Kauffman, Ge, Xie, and Chen (2008) provided prompts to guide their analysis of those cases, including:

- What do you see as the primary problems with this classroom? Why are they occurring?
- Can there also be some other problem(s)? Why or why not? What can they be?
- What are some of the specific examples of the problem you see that can be used to help Cindy to understand the classroom management issues?
- What specific strategies do you want to suggest to Cindy to help her address the problems you have identified in her classroom and to improve the students' focus and concentration on academics?
- Why do you suggest those strategies? Use examples or evidence to support your suggestions.

As you can see, these prompts were specific to the case. Following the students' responses to the case, they engaged reflections on student answers with the following prompts in a Likert scale format:

- You identified the primary problem successfully?
- You successfully identified all other possible problems?
- You suggested the best strategies to solve the problem?
- The solutions you suggested will help alleviate the problem?
- Your email to Mrs. Green is understandable and flows coherently?

Students receiving embedded problem-solving prompts solved case-study problems better than those who did not. Using embedded problem-solving prompts in problem-solving contexts improves students problem-solving performance (Ge & Land, 2003).

Many of these metacognitive prompts focus on the problem-solving processes. Because problem solving requires conceptual engagement, I believe that metacognitive prompts should reflect the kinds of conceptual supports described throughout this book. For example:

- Have I seen a problem like this before?
- What kind of problem is this?
- How is it similar to, or different from, those problems that I have solved?
- What lessons did I learn from solving that problem?
- Can you show me an example of how to solve it?
- Can you show me a (structurally) similar problem?

- What will happen if I . . . ?
- What other perspectives should I consider before thinking of a solution?
- What are the elements of this problem?
- How do those elements relate to each other?
- Are there stories of people solving similar problems?
- How much do I know about the ideas in this problem?
- What kind of problem is this?
- What are the factors and attributes in this problem?
- Do all of these elements belong? Are all of them necessary to solve the problem?
- How are they related to each other?
- What is the most effective way to represent this problem?

An examination of each chapter in this book can provide numerous metacognitive prompts. A great many research questions related to the nature of the metacognitive prompts and students' understanding of and ability to solve different kinds of problems have yet to be examined. Similar to feedback research, the timing and placement of metacognitive prompts deserves a large number of research studies. Should prompts be placed before, after, or during learning? How often? What form should the prompts take?

Another fruitful line of research in online problem-solving learning environments involves the use of pedagogical agents. Animated lifelike pedagogical agents (Lester, Stone, & Stelling, 1999) can be used to monitor and provide metacognitive support during problem solving. The agent could help the learners to reflect on the problem after reading it, helping the learner to look for clues to help to classify the problem type or determine the necessary problem elements and relationships. Based on audit trails, the agent might suggest perspectives that the learner has not considered before proposing a solution. The agent may provide stories to help learners interpret the problem or different solutions. It may provide feedback on a proposed solution. The possibilities are endless, and the potential of pedagogical agents barely tapped.

PART IV

ASSESSING PROBLEM SOLVING

22

ASSESSING PROBLEM SOLVING

WHAT ARE THE PROBLEMS IN PROBLEM SOLVING ASSESSMENT?

Assessment is probably the most important component in formal education. Students know strategically that what is important is what gets assessed. Irrespective of stated goals, objectives, missions, curricula, or any other descriptor of learning outcomes, what is “on the test” is what is important to students. Their strategic knowledge is based on the assumption that what is “on the test” is what is important to teachers, professors, and trainers. Unfortunately, that is not a good assumption. What is important to teachers, professors, and trainers often has little to do with the kinds of assessments they use. They hope that their students can think critically and solve problems, but they just do not know how to design and implement quality assessments of problem solving. That is, assessment is the weakest link in learning to solve problems (as well as most other tasks and venues).

Probably the fastest way to enhance learning in schools, universities, and corporate training venues is to implement assessments that assess meaningful learning, such as problem solving. Students would then know that meaningful learning, rather than memorization, is important. However, constructing, implementing, and evaluating meaningful assessments are a complex set of skills that most educators do not possess. Even when assessment skills are available, few educators are willing to commit the effort required to construct, implement, and evaluate meaningful assessments. In short, it is hard work, so constructing recall test items becomes the default method of assessment. The assessment process is even more difficult because assessing meaningful learning, such as problem solving, requires more than one form of assessment. Most courses or classes in K-12, university, and corporate training employ only a single form of assessment to assess learners' knowledge, skills, and abilities. Educators most often use quizzes, examinations, or papers to assess student understanding, and they assign grades or evaluations based on only one form of assessment of knowledge and skills. Single forms of assessment betray the richness and complexity of problem solving. Throughout this book, I have described the multiple ways of knowing that are required to solve problems. The reality is that the ability to solve problems and to transfer problem-solving knowledge and skills to novel problems cannot be adequately assessed using any single form of assessment. If we hope to discover whether learners are able to transfer problem-solving knowledge and skills, we must use multiple forms of assessment. When we ask learners to represent what they know and know how to do using only a single form of assessment, we necessarily constrain their understanding of whatever they are studying. Students in all levels of education have deficient understanding of content and skills because they were required to represent what they know in only one way.

The point is obvious. Using appropriate forms of assessment is critical to learning to solve problems. If we teach students to solve problems but assess only their ability to recall what they have memorized for a test, then students will not invest mental effort in learning to solve problems. One of the foundational assumptions of instructional design is that the conditions of learning should match the learning outcomes and the form of assessment. So our assessment needs to be congruent with problem-solving outcomes that we teach. Adequate assessment of problem-solving skills requires more than one form of assessment. The ability to solve problems and the cognitive residue of that experience cannot be adequately assessed in only one way. I would argue that nothing worth knowing can be adequately assessed using any single form of assessment. There are many ways to assess problem solving. In this chapter, I describe four different ways of assessing problem solving knowledge and skills (see Figure 22.1) including:

1. Assess problem schemas (problem types).
2. Assess their problem-solving performance.

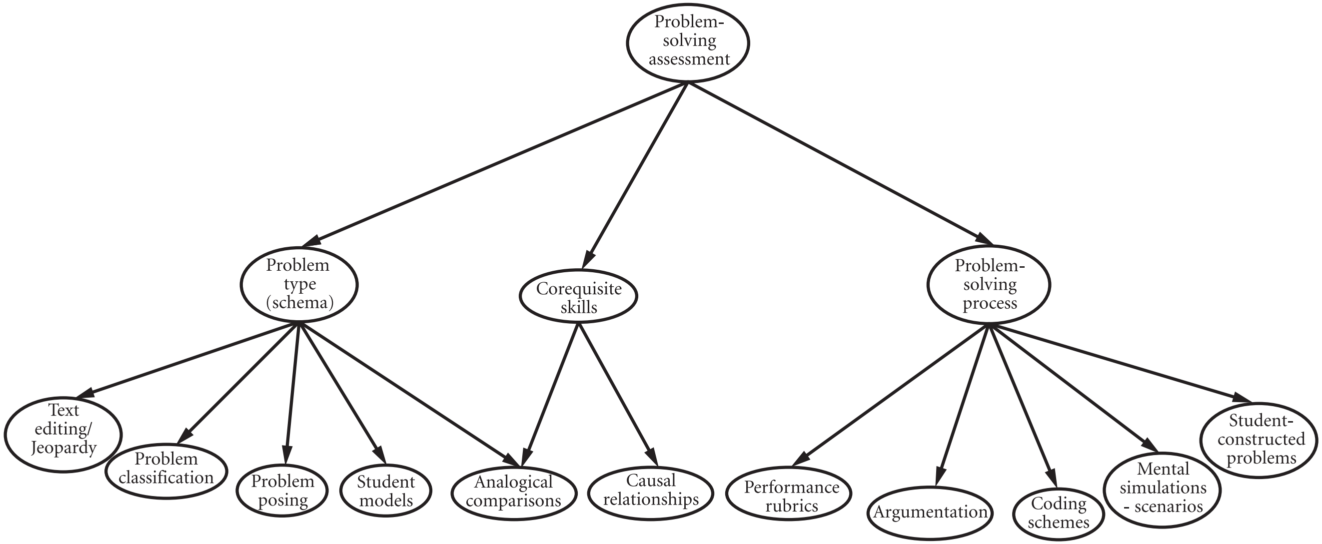


Figure 22.1 Forms of problem-solving assessment.

3. Assess the component, cognitive skills required to solve problems (e. g. understanding of domain concepts and causal reasoning).
4. Assess their ability to construct arguments in support of their solutions to problems.

Each of these forms of assessment requires different cognitive skills. I recommend using some form of all four assessments when assessing problem solving. I will describe each of these forms of assessment in this chapter. Remember, if you want your students to learn to solve different kinds of problems, you must learn to teach them to solve problems and then assess their different abilities to solve the kinds of problems that they practiced. The problems should be the same level of difficulty.

HOW DO WE ASSESS PROBLEM SCHEMAS?

In Chapter 15, I described how important the mental construction of robust problem schemas are to problem solving. A problem schema enables learners to determine what kind of problem is being solved. A problem schema contains structural and situational characteristics of the problem in addition to processes for solving the problem. In this section, I describe methods for assessing the quality of the learner's problem schema. Because a robust schema is essential to problem-solving transfer, the quality of a problem schema is predictive of problem-solving ability. Note that these methods are most useful for well-structured problems that are found in math and the sciences for which definitive problem types can be identified. For more ill-structured problems, where the problem characteristics are less predictable, assessing problem schemas becomes less predictable. Which kinds of problem are amenable to problem-schema assessment has not been determined by empirical research.

How Do We Use Problem Classification Questions to Assess Problem Schemas?

If students have constructed robust problem schemas for the problems they are learning to solve, then they will be able to accurately classify the problems. For example, present a problem such as that in Figure 22.2.

Rather than asking students to solve the problem, ask them to classify the type of problem, as, for example, kinematics, Newton's second law, work–energy, etc. (Chi, Feltovich, & Glaser, 1981). Science courses are normally taught as a sequence of problem types, so the first week in a physics course (typically kinematics), you would ask, "Is this a

Problem A
A 0.10 kg arrow is fired from a bow. The bow is pulled back a distance of 0.8 m so that the arrow is released with a speed of 50 m/s as it leaves the bow. The arrow travels 25.0 m before hitting its target. What is the average force exerted on the arrow by the bowstring?

Figure 22.2 Physics problem used for problem classification.

kinematics problem or not?" For Week 2 (work–energy, for example), you would present problems and ask which of the two types (kinematics or work–energy) the problem exemplifies. Each week, you add another problem type to the list of possible classifications.

Problem-classification exercises are useful for helping students to construct more robust problem schemas, because students tend to generalize problem schemas based on surface-level similarities among problems rather than the physics principles used by experts (Chi et al., 1981; Dufresne, Gerace, Hardiman, & Mestre, 1992; Hardiman, Dufresne, & Mestre, 1989). Any efforts to help students to classify problems based on their structural characteristics will enhance students' problem-schema development.

Another related method for assessing problem classification is the card sort or question sort. Rather than asking students to solve a set of problems, simply present the problems and ask students to sort them into conceptual piles. You should ask students to explain the reasoning behind their groupings, especially in terms of physic concepts and principles. Again, experts tend to group problems by laws of physics, and novices based on surface features (Chi et al., 1981).

How Do We Use Text Editing/Jeopardy Questions to Assess Problem Schemas?

Text editing is a method (described also in Chapter 15) for assessing the quality of problem schemas. Text-editing questions (Low & Over, 1989; Low, Over, Doolan, & Michell, 1994; Ngu, Lowe, & Sweller, 2002) present standard questions such as those in Figures 22.3 to which a quantity has been added or deleted or left alone (see example in Figure 22.3). Students are required to identify whether the problem contains sufficient, irrelevant, or missing information. Students cannot answer such questions unless they understand what kind of problem it is and what elements are appropriate for that kind of problem. While they appear fairly simple, these questions are difficult for students to

Jane, looking for Tarzan, is running at top speed (4.0 meters per second) and grabs a vine hanging vertically from a tall tree in the jungle. How high can she swing upward?

For this problem,

1. There is insufficient data presented to solve the problem.
2. There is sufficient data presented to solve the problem.
3. There is more information presented than is needed to solve the problem.

Figure 22.3 Text editing question to support problem schema development.

answer, especially if the students are required to explain their answers. Because students are asked to complete the tasks without solving the problem, students need to know the interrelationships between various physical quantities, not in terms of equations, but at a conceptual level to be able to successfully complete the task.

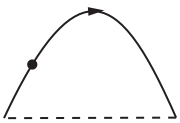
A variation on text editing is a jeopardy problem, modeled after the popular television quiz show of the same name. Physics jeopardy tasks were first developed by Van Heuvelen and Maloney (1999). As the game show requires, these tasks require the students to work backward. Students are given a fragment of a solution to a problem and asked to identify the physical scenario that corresponds to the solution. The developers point out that these tasks require an effort to represent a physical process in a variety of ways. Because of these features, students are unable to use naive problem-solving strategies while solving jeopardy problems. Figure 22.4 below shows an example of an adaptation of a jeopardy problem that provides students with a few steps of a projectile motion. Students are asked to determine what trajectory shown

34. (2 points) You are given below a worked-out solution to a kinematics problem.

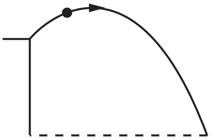
Step 1: $x = x_0 + v_{x0}t$	Step 2: $y = y_0 + v_{y0}t + \frac{1}{2}a_y t^2$
Substituting known values, we get:	Substituting the value of 't' from Step 1, and other known values we get:
$90.0m = 0 + (26.0m/s)t$	$0 = y_0 + (15.0m/s)(3.46s) + \frac{1}{2}(-9.8m/s^2)(3.46s)^2$
Solving for 't' $t = 3.46s$	Solving for 'yo' $y_0 = 6.80m$

Identify the diagram that correctly represents the situation of the problem.

(a)



(b)



(c)

(d)

(e) None of the diagrams above correctly represent the situation of the problem.

Figure 22.4 Physics jeopardy problem.

corresponds to the problem. This task requires students to relate information given in the mathematical and symbolic representation to a visual or pictorial representation.

How Do We Use Problem Posing to Assess Problem Schemas? Problem-posing tasks were used by Mestre and others (Mestre, 2002) in the context of physics problems. In the tasks presented by Mestre, students were given a scenario, typically in the form of a picture, and were asked to construct a problem around the scenario that was based on certain physical principles. Mestre points out problem-posing tasks are aimed at probing students' understanding of concepts as well as assessing whether they transfer their understanding to a new context. Clearly such a task was rather open-ended with multiple possible answers.

> Take a look at Figure 22.5 below. Create your own physics problem based upon this situation. You may use anything that you have learned from general physics.

A variation on the problem-posing task is to give students a statement describing a situation and to ask them to add a question that would turn it into a problem that uses specified principles or equations. It presents students with the first part of a problem statement that

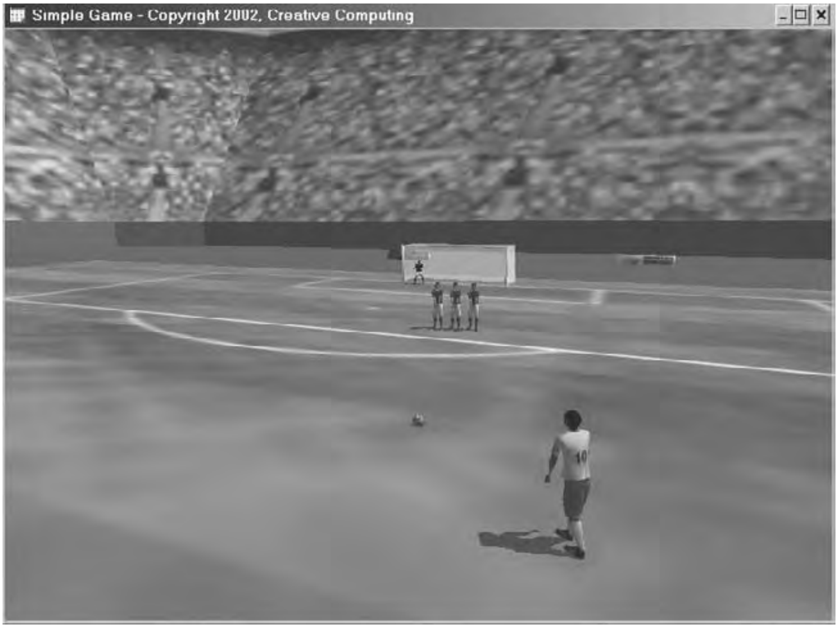


Figure 22.5 Problem-posing stimulus.

clearly describes a physical scenario. Students are then asked to select from a list of choices, a question, which when added to the statement will create a solvable problem that requires the use of a set of given equations. Clearly, our adaptation differs significantly from the original problem-posing task designed by Mestre. First, this task clearly does have a unique correct answer. Second, it requires the knowledge of specific conceptual knowledge, represented in the form of equations. For example, see Figure 22.6.

How Do We Assess Student Models?

In Chapter 19, I described different tools for constructing models of problems, including semantic networking, expert systems, influence diagrams, and systems models. In the context of that chapter, the purpose for using those tools was to help learners to construct models of the problems space in order to understand the problems better. However, the models that students build can also be used to assess learners' problem schemas. Don't be afraid to substitute them for examinations.

If you use the models that students construct as assessments, then you will need to construct rubrics for assessing their models. Those rubrics should address the quality of the models themselves. For example, rubrics for assessing expert systems constructed by students might include dimensions such as in Figure 22.7.

In addition to these criteria, problem-specific and discipline-specific criteria would need to be used to assess the quality of the problem schema. While writing rubrics to assess these models may be more difficult, the benefits of model building should justify the effort. Additionally, assessing the models will convey their importance to students.

You are given the starting statement of a problem below.

> A 500-kilogram cargo shipment, attached to a parachute, drops vertically out of a helicopter hovering 100 meters above a large spring (k = 220,000 N/m). The cargo comes to rest when the spring compression is 0.50 meters.

Which question, when added to the statement above, will make a solvable problem that *requires ALL of the following* equations to solve?

$W = Fd \qquad W = \Delta KE + \Delta PE \qquad PE_{spring} = \frac{1}{2}kx^2 \qquad PE_{gravity} = mgy \qquad KE = \frac{1}{2}mv^2$

1. What is the speed of the cargo just before striking the spring?
2. How much time does it takes for the cargo to make contact with the spring?
3. What is the work done by air resistance acting on the parachute as it drops?
4. What is the average force of air resistance acting on the parachute as it drops?
5. None of the above.

Figure 22.6 Alternative problem-posing question.

Quality of decisions/solutions/advice	Advice would never be given (implausible); solutions missing or not elaborated; conclusions not useful	Advice is plausible; all solutions identified; provide meaningful solutions
Explanations meaningful	Explanations of results are vague; do not explain reasoning or enhance learning	Explanations of advice explains reasoning, enhances users' understanding
Sensitivity of factors (questions)	Factors don't discriminate solutions; variables and factors missing; factors overlap	Ask important questions; identify all variables that pertain to solution; each factor elicits different information
Rules logical and complete	Running system results in dead ends; combinations not anticipated; not enough rules; rules poorly organized	All combinations of factors represented by a rule; all dead ends blocked; rules well organized
Meaningful representation of thinking	Poorly simulates thought; poor models of activity; represents associative thinking	Simulates coherent thinking; models meaningful activity represents causal/predictive reasoning

Figure 22.7 Criteria for assessing student-constructed expert systems.

How Do We Assess Analogical Comparisons of Problems?

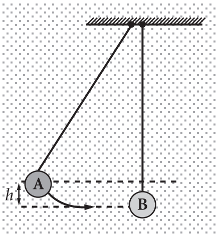
Analogical comparison of problems requires that learners identify structural similarities and difference between pairs of problems. The simplest method for this comparison is to present pairs of problems and to ask learners to identify on a scale how similar the problems are (Littlefield & Rieser, 1993; Low & Over, 1989, 1990, 1992). Hardiman et al. (1989) compared novices and experts on similarity judgment task and found, like other studies, that experts relied on deep structure, while novices on surface similarities.

Another form of analogical comparison question is to present a pair of problems and ask students to identify problem elements and similarities and differences between the problems (see Figure 22.8). Those comparisons may be prompted with multiple-choice questions or left to the student to identify (a more robust form of assessment, albeit harder to score).

Analogical comparisons also comprise an important cognitive skill in problem solving (see Chapter 16). These kinds of analogical questions may also be used to assess that skill.

PROBLEM 1

Two pendulum bobs (see figure) are made of soft clay so that they stick together after impact. The mass of bob A is half of that of bob B. Bobs A and B are initially at rest, with bob A starting at a height *h* relative to bob B. What is the merged blob (A+B) speed immediately after the collision?



PROBLEM 2

A 10-g bullet traveling at a speed $v_0 = 76$ m/s is fired towards a 1-kg block of wood supported by an ideal wire. The bullet penetrates the block of wood where it gets embedded. What is the speed of the bullet + block system immediately after the collision?

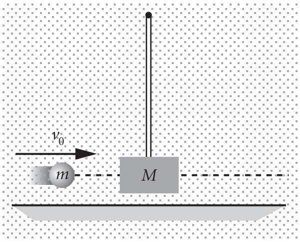


Figure 22.8 Problem pair for comparison.

HOW DO WE ASSESS COGNITIVE SKILLS IN PROBLEM SOLVING?

In Part III of this book, I describe a number of cognitive skills that are required to learn to solve problems. Each skill, by itself, is insufficient for learning to solve problems. Whether each skill is necessary for solving each kind of problem is unknown. The cognitive skills that are necessary for solving each and every kind of problem are analogical reasoning and causal reasoning. Analogical reasoning (see Chapters 11 and 16) is necessary for inducing robust problem schemas. Methods for assessing those analogical comparisons were just described. In addition to assessing the quality of problem schemas, problem-solving ability can be predicted by assessing students' understanding of the causal relationships between problem elements. I briefly describe how to assess causal relationships next.

How Do We Assess Causal Reasoning?

In Chapter 17, I explicate the centrality of causal reasoning to problem solving. From a cognitive-processing perspective, problem solving is largely a process of understanding the causal relationships among the problem elements and making inferences about what caused a certain state or predicting what state will result from a set of conditions. That is, problem solutions are effects that result from causes. Asking questions about those causal relationships will focus students' attention on conceptual, qualitative understanding of the problem elements. In Chapters 17 and 18, I illustrated a number of questions that engage causal reasoning (please see those examples). In addition to helping students understand problems, they can also be used to assess student understanding of the causal relationships in a problem.

In order to ask causal questions, it is necessary to present a scenario and to ask students to make an inference or prediction based on that scenario. That is, it is necessary to ask students to apply the causal relationship in a new situation. It is much easier to ask students about the relationship. In order to elicit causal reasoning, students must apply the relationship. For example the following question (in multiple-choice format), requires an inference.

> You have just received a shipment of three boxes, each containing one of the isotope sources for the three nuclear thickness gauges described above. Each box has a radioactive-material label affixed. The sources all weigh the same amount. The boxes are the same size but have different weights. What is the likely reason for the different box weights?
>
> 1. The sources each emit radiation of different energy, so they each weigh differently because of the different shielding needed.
> 2. The sources each emit radiation of different penetrating ability, so they each weigh differently because of the different shielding needed to attenuate the radiation from each source.
> 3. The sources each have a different amount of radioactivity, so they each need a different amount/weight of shielding depending on the amount of radioactive material.
> 4. The sources each have a different half-life, so they each need different shielding depending on the half-life.

Likewise, in order to elicit prediction performance, it is necessary to provide a scenario and ask students to do the following:

> Suppose that a sample of 238U is allowed to come to equilibrium with all of its daughters in its decay chain and then the 226Ra is chemically removed from the sample. What will happen to the activities of the isotopes in the decay chain starting with 226Ra and its daughters as time increases? Check the one best answer.

1. They will all decrease because the 226Ra has been removed.
2. They will increase because the decay of the parent of 226Ra (e.g., 222Rn) will decay producing more 226Ra and all of its daughters.
3. The activity of 226Ra will increase due to the decay of its parent, 222Rn, but there will be no increase in the activities of the daughters of 226Ra.
4. There will be no increase in the activity of any of the isotopes in the decay chain following 226Ra.

If students are unable to answer question such as these, it is unlikely that they will be able to solve problems. Note that these examples of causal questions are multiple choice. They could also be presented as open-ended questions that require students to construct and answer, a process that would require more mental effort.

In addition to generating questions to assess causal reasoning, student models (see Chapter 19) may also be assessed. The best tools for constructing causal models are causal maps (influence diagrams).

HOW DO WE ASSESS PROBLEM-SOLVING PERFORMANCE?

The concept of performance assessment is easy: "Can the students perform the task?" Not "Do they remember how to solve problems?" Not "Do they remember the domain content required to solve problems?" Can the students solve problems similar to the ones they have been taught? Can they perform problem solving? How well was the problem solved? Performance assessment includes these elements (Elliott, 1995):

- Students must construct a response or a product, rather than simply select from a set of predefined alternatives or answers.
- Assessment consists of direct observation or assessment of student behavior on tasks or on the product that they produced.

To these, I add a third. Assessment also requires the assessment of the quality of the solution using some sort of description of desirable performance, called a rubric. Solving any kind of problem requires multiple operations or actions and different kinds of skills and knowledge. For example, oral reports in a typical classroom are mysteriously *graded* (neither students nor teachers can really tell you where the grades come from), and few comments generally accompany the grade. So students typically know only what grade (evaluation) they received but not which aspects of the performance were responsible for that grade.

How Do We Use Rubrics to Assess Problem-Solving Performance? Many problems, especially in the sciences, require students to generate and derive equations to determine the correct answer. In such problems, successful learners produce the correct answer and demonstrate the derivations of equations in the correct sequence to produce the correct answer. Although usually unstated, the criteria for assessing this kind of problem solving include the correct answer and the correct sequence of equations. I believe that it is necessary to more clearly articulate the requirements for an acceptable answer. The most common method is to construct performance rubrics that describe the levels of acceptable and unacceptable performance.

Writing and using rubrics is hard work. So why do it? The obvious answer is to communicate the parameters of a good solution to a problem. Rubrics were not originally developed as summative assessment tools, that is, methods for grading student responses. Rather, they were designed to provide feedback to students in a formative manner that would enhance the quality of their performance. However, they can be used to communicate final requirements and summatively assess student performance.

Another reason for writing rubrics is a bit more challenging. If you as a teacher, professor, or trainer are unable to articulate the desired elements of some required performance, then you have no business assessing student performance. If you cannot even describe what proper performance is, how can you make informed, meaningful judgments about the quality of student performances? Most people recognize an excellent performance when they see it but often are unable to say why the performance was excellent. That is not adequate for assessment purposes. Conversely, if you are unable to articulate the required elements of any performance, it is unlikely that you will be able to teach those performances well.

Rubrics can be constructed to assess any kind of problem solving. As indicated in Chapter 2, most story problems require learners to understand the nature of the problem, to select an appropriate formula to represent the problem, to insert the values from the problem into the formula, and to solve the formula for a specific value. Most story problems are assessed based on whether the student produces the correct value for an answer. I argue that rubrics should also be used to articulate the ability of students to understand the kind of problem being solved and also the nature of the structural relationships embedded in the problems.

A policeman chases a master jewel thief across city rooftops. They

> are both running at 5 meters per second when they come to a gap between the buildings that is 4 meters wide and has a drop of 3 meters. The thief, having studied a little physics, leaps at 5 meters per second and at a 45 degree angle and clears the gap easily. The policemen did not study physics and thinks that he should maximize his horizontal velocity, so he leaps at 5 meters per second horizontally. Does he clear the gap? By how much does the thief clear the gap? What type of problem is this? Show all actions, assumptions, and formulae used to answer these questions.

In this example, the student must classify the problem type, identify initial conditions, set up the equation, estimate the answer, and solve the equation. Rubrics can be created for assessing the student's solution method because the students are required to show their work. These operations define the nature of the required rubrics. For story problems, the primary rubric focuses on the correctness of the answer. Some possible rubrics for assessing physics problem solving may include:

Accuracy of Problem Classification

Misclassified problem.	Identified correct group, but misclassified specific problem type.	Correctly classified the specific problem type.

Identification of Initial Conditions

Unable to identify any initial or final conditions.	Identified some initial or final conditions.	Correctly identified all initial and final conditions in problem.

Accuracy of Equation

Used wrong equation or misplaced all values.	Used correct equation by misplaced some values.	Equation set up correctly with values in correct places.

Accuracy of Answer Estimate

Estimate of answer the wrong order of magnitude.	Estimate right order of magnitude but wrong sign or not close to final answer.	Estimate of answer very close to final answer.

Unit Consistency

Units completely mismatched.	Units mixed; some correct.	Correct units used and cancelled.

Accuracy of Answer

Answer is quite different from correct.	Answer is close to correct answer; arithmetic operation suspected.	Answer is exactly correct, to the nearest hundredths.

Needless to say, the nature of the rubrics will differ with the discipline and the nature of the problem. The rubrics must address the specific performances required by the problem. These can only be used when students' responses include some evidence of their thinking.

For more complex and ill-structured problems that do not have universally accepted answers, the use of rubrics is more important in assessing student performance. We are implementing a problem-based curriculum in an introductory material-science course in the mechanical engineering curriculum. Students will learn by solving decision-making and troubleshooting problems. In the decision problem abstracted below, students must determine the performance problem, determine the material properties needed to meet performance requirements, calculate performance requirement, select and evaluate candidate materials, and construct an argument in support of their decision.

> **Improved Design of Cassette Plates**. You have been asked to redesign X-ray film cassettes so that they are lighter but retain the same stiffness to bending loads. Compare various materials that are compatible with the application to produce an improved cassette.

For this kind of problem, we use the following rubrics (along with others) for assessing student reports. Note that their reports are not constructed during time-pressured examinations. Any kind of performance, including examination performance, can be assessed using rubrics. A corollary is that assessment of student knowledge and ability need not always occur in examinations.

Determination of Performance Problem

3. All performance characteristics of problem (e.g., weight, speed, structural strength, thickness, stiffness, higher or lower

temperature) identified; all characteristics relevant to problem.
2. Most performance characteristics identified; all relevant to problem.
1. Only a few performance characteristics identified; some not relevant to problem.
0. No performance characteristics identified.

Required Performance Characteristics

4. All performance characteristics stated using appropriate descriptors (e.g., lighter, stronger, faster, bending stiffness, X-ray transmission).
3. Most performance characteristics stated, all with appropriate descriptors.
2. Most performance characteristics stated, some with appropriate descriptors.
1. Few performance descriptors stated.
0. No performance descriptors stated

Material Properties (for each performance characteristic)

3. All primary and secondary material properties identified for each performance characteristic.
2. Most primary and secondary material properties identified for each performance characteristic.
1. Some primary and secondary material properties identified for each performance characteristic.
0. No primary and secondary material properties identified for each performance characteristic.

Interactions Among Material Properties on Performance Stated Correctly

3. All interactions among material properties on performance stated correctly (e.g., increasing the thickness will increase the stiffness but may increase the weight).
2. Most interactions among material properties on performance stated correctly.
1. Some interactions among material properties on performance stated correctly.
0. No interactions among material properties on performance stated correctly.

Interactions Among Material Properties on Performance Stated Correctly

3. All interactions among material properties and performance correctly quantified using appropriate equations.
2. All interactions among material properties stated but equations are not all accurate.
1. Some interactions among material properties and *performance* correctly quantified using appropriate equations.
0. No interactions among material properties correctly quantified using appropriate equations.

For Specific Material Selected

3. Correct calculation of changes from a baseline.
2. Partially correct calculation of changes from a baseline.
1. Inaccurate calculation of changes from a baseline.
0. No calculation of changes from a baseline.

For even more complex and ill-structured problems, writing rubrics can become even more difficult. For instance, consider the policy-analysis problem (see Chapter 6):

> Water-borne diseases. Most public water supplies are routinely monitored, but private supplies may not be subject to the same quality standards. In the Russian Federation, half the population uses water that fails to meet quality standards. In Latvia, 55% of water samples from shallow wells fail to meet microbiological standards. Yet half the rural population relies on these wells as a source of drinking water. In Albania, twenty-five people died of cholera in 1994 after drinking contaminated water. In Latvia, several hundred cases of hepatitis A and bacterial dysentery are attributed to contaminated drinking water each year. In Tajikistan, some 4,000 cases of typhoid fever were reported in 1996 following heavy rainfall. In the past decade there have been some 190 outbreaks of bacterial dysentery, seventy outbreaks of hepatitis A and forty-five outbreaks of typhoid fever associated with drinking water and recreational water in Europe and central Asia. More than 5 million people, most of them children, die every year from illnesses caused by drinking poor-quality water. Advise the Secretary General of the United Nations what actions should be taken by the UN.

It is likely that your students would individually or collaboratively write position papers to deliver at the UN Council as well as white papers that advise the Secretary General. Because of the complex nature of the problem, the nature of the assessment for such a problem will depend on the nature of the specific problem that you posed to the students. The nature of the rubrics will depend on the nature of the task. If students were to write a policy paper for the UN Secretary General, some rubrics for assessing the paper might include:

Quality of Information Sources Cited

Sources of information in report unknown.	Sources of information in report were questionable and not well established.	Sources of information in report were internationally recognized.

Constraint Analysis

Solution considered few, if any, social, political, and economic constraints.	Many constraints identified; unequal balance among sources.	All known social, political, and economic constraints identified in report.

Economic Feasibility

Solution recommendations are economically impossible.	Solution recommendations have unclear economic implications.	Solution recommendations are feasible within current economic constraints.

Relevance of Political Implications

Few, if any, political implications identified.	Political implications identified but unclear how they affect situation.	Political implications are clear and feasible within current political context.

Of course, many, many other rubrics could be constructed to describe such a complex performance, including all of the quality issues surrounding the writing of the report. The nature of the rubrics that you construct to assess any activity should emphasize the aspects of the performance that you deem most important.

How Do We Use Coding Schemes to Assess Problem-Solving Processes?

All of the rubrics described before were used to assess the products of student performance (papers, exams). Rubrics can also be used to assess processes as well as products. Another way to assess policy-analysis problem solving is to observe and assess the problem-solving process. Audiotaping or videotaping the problem solvers while they are solving problems and transcribing those tapes leaves you with a verbal protocol to analyze. Atman and Turns (2001) described a series of verbal protocol studies where they observed engineering students engaged in design tasks (see Chapter 7). Students would think aloud (Ericsson & Simon, 1993) while solving the problem. They developed a coding scheme (see other examples in Chapters 20 and 21) including:

- identification of need;
- problem definition;
- gathering information;
- generating ideas;
- feasibility analysis;
- evaluation;
- decision;
- communication;
- implementation.

Each thought uttered by students as they solved design problems aloud was classified according to one of these codes. The codes that Atman and Turns used were meant to characterize the cognitive activities engaged by design problem solving. Different kinds of problem solving would require different codes. Atman and Turns (2001) found that older students (seniors) identified more criteria, had significantly more transitions between design steps, and gathered more information than younger students (freshmen). Verbal-protocol analysis is a more difficult kind of analysis, but it exposes student reasoning better than most other forms of assessment. After coding protocols, you really understand the students.

The verbal-protocol-analysis process is made easier when the discussions are online, because each message and its producer are already identified, and the contents of the discussion forum can be saved in a database. Cho and Jonassen (2002) analyzed each of the messages posted during problem-solving sessions by classifying each message based on a problem-solving coding scheme, the Decision Function Coding System (DFCS) adapted from Pool and Holmes (1995). The DFCS consists of seven categories, including:

1. problem definition (PD);
2. orientation (OT);
3. criteria development (CD);
4. solution development (SD);
5. solution approval (SA);

6. solution critique (SC);
7. non-task statement (NS).

That is, we classified the purpose of each message according to this scheme. We found that providing a constraint-based argumentation scaffold during group problem-solving activities increased the generation of coherent arguments, and that groups who solved ill-structured problems produced more extensive arguments. The nature of the coding scheme could be changed to focus on the required elements of the problem. For instance, we could have used constraint analysis, political implications, or any other element required in the solution. These codes, in effect, represent rubrics, so you as the teacher are coding student responses in terms of desired behavior.

Jonassen and Kwon (2001) used a similar coding scheme to compare problem-solving processes used in computer-mediated communication vs. face-to-face communication. We found greater use of non-task, simple agreement (corresponding to solution approval), and simple disagreement (corresponding to solution critique) categories for both well-structured and ill-structured tasks in the computer-mediated group, relative to the face-to-face group. That is, the nature of the task did not have a significant effect on the problem-solving processes used by students. That is why Cho and Jonassen (2003) scaffolded problem-solving skills. Coding messages or interactions observed while students are problem solving provides valuable information about the nature of problem solving that students performed. Again, the emphasis in all of these methods is to analyze performance.

How Do We Assess Problem Solving Using Argumentation?

Because argumentation is an implied component in every kind of problem solving (see Chapter 20), students' argumentation about how and why they solved problems as they did provides perhaps the most powerful form of problem-solving assessment. If students can argue effectively about their solutions to problems, how they solved the problem, or why they did what they did, they provide confirmatory evidence about their problem-solving ability. As indicated at the beginning of the chapter, the most complete assessment of problem solving will combine argumentation with performance assessments and assessments of constituent cognitive skills.

Student arguments can be collected using a variety of methods. Argumentation can be measured using objective forms of measurement such as multiple-choice questions, performance rubrics for essays, or verbal protocol analysis.

How Do We Use Objective Forms of Argumentation to Assess Problem Solving?

Argumentation skills can also be assessed using objective forms of assessment, such as multiple-choice tests. Questions requiring argumentative reasoning can form the stem of a test item. For example:

> Students who work harder in school will make a better living after school. Which is the most appropriate assumption on which this premise and conclusion are based?
>
> 1. Attitude is the most important difference; those who work harder get more.
> 2. What your teachers think of you is the strongest predictor of success.
> 3. Skills acquired in school better prepare you to function in the real world.
> 4. The harder you work, the more you know.
>
> Which conclusion logically follows from the following premise: the Stock Market has fallen 200 points in the past week.
>
> 1. Buy more stock; it's a bargain.
> 2. Sell all of my stock; the economy is broken.
> 3. The economy is inflationary.
> 4. Consumer confidence is down.

These questions focus on the evidence to support the claims stated in the question stem. Similar questions can also be developed to specifically assess the arguments required to solve a particular kind of problem. There is no research on the use of this form of assessment and its relationship to problem solving. Although this form of assessment is easy, it probably will not provide sufficient evidence of problem-solving ability if used alone.

How Do We Assess Student Essays?

Given any problem, especially ill-structured ones, students are most often required to articulate and justify a solution. Assessing those essays requires the construction and application of argumentation rubrics. This method requires reading and evaluating students' argumentative essays using those rubrics, which are based on the strength of relationships between premises, conclusions, assumptions, and counterarguments (Halpern, 2003). Norris and Ennis (1989) suggested the following criteria for evaluating argumentative essays:

- Do you clearly state the conclusion and define the necessary terms?

- Are the materials that you included relevant to the conclusion?
- Is the argument sound? Do the premises support the conclusion?
- Have you considered the credibility of your experts?
- Is the essay well organized with each argument laid out separately?
- Have you fairly represented opposing points of view and counterarguments?
- Have you used good grammar and a clear style of writing?

Below, I synthesize a series of assessment rubrics for assessing the quality of students' argumentative reports or essays based on Halpern's (2003) conception of arguments. When students construct arguments as part of the problem solution or as an addendum to their solutions, you might use these rubrics, along with discipline-specific rubrics to assess the quality of their arguments.

Quality of Conclusions (claims)

Conclusions unrelated to problem needs or solution.	Few conclusions relate to problem needs or solutions; inconsistent relationships.	Conclusions relate to problem generally, but some unclear; usually support stated solution.	All conclusions relevant to problem; support solutions; related to needs.

Premises are Sound

Premises not related to conclusions.	Relationship of premises to conclusions is inconsistent; not related well with other premises.	Most premises support conclusion.	All premises support specific conclusion; add strength to the conclusion; consistent with other premises.

Adequacy of Premises

No premises stated; only unsupported conclusions.	Few premises stated; most unclear.	Most premises stated explicitly; most clear.	All premises stated explicitly and clearly.

Assumptions Related

Completely unstated and unknown.	Few stated but not associated with premises or conclusions; mostly unreasonable or invalid.	Most assumptions stated; not all connected to conclusions or premises; some invalid.	Clearly stated; consistent with claims and premises; reasonable and valid.

Credibility of Premises

Sources of evidence are weak, filled with unsupportable evidence and propaganda.	Sources of evidence are questionable or origin is unknown.	Sources of evidence mostly valid with limited amounts of unknown data.	Sources of evidence (personal, written, etc) are unimpeachable; accepted as fact.

Counterarguments Accommodated

No counterarguments acknowledged.	Only one or two counterarguments acknowledged; none argued or rejected.	Most counterarguments addressed; refutation not premise-based.	All counterarguments identified and refuted using valid, supportable premises.

Organization of Arguments

Arguments are indistinguishable; unorganized; do not support each other.	Arguments identified; relationships to each other not obvious.	Arguments articulated but partially integrated; relationships to each other usually positive.	Each argument separated; sequenced logically to support solution to problem.

Student essays or individual verbal or written accounts of problem solving may also be assessed using rubrics based on Toulmin's conception of argumentation, which focuses on claims, supported by warrants, supported by backing or evidence. Cho and Jonassen (2002) scored individual reports of how problems were solved using the scoring rubric below in order to determine the quality of argumentation based on Toulmin's (1958) model of argument. Individual scores were achieved by summing the number of points achieved in each argumentation category (claims, grounds, warrants, backings, and rebuttal).

Claims

No claim related to the proposition or unclear assertions.	The writer makes generalizations that are related to the proposition, but the assertions lack specificity or offer unclear referents. The writer leaves much for the reader to infer in order to determine the impact of the claim.	The writer states generalizations that are related to the propositions, but the assertions are not complete. Enough information is available to figure out the writer's intent, but much is left to the reader to determine.	The writer states generalizations which are related to the proposition and which are clear and complete.

Grounds

No supporting data are offered or the data are not related to the claim.	The data or evidence are weak, inaccurate, or incomplete. E.g. a) an attempt at using a general principle without establishing the truth of the principle; b) the use of examples from personal experience which are not generalizable; c) the citation of data when no source is identified; and d) the use of obviously biased or outdated material.	The data offered are relevant but not complete. The writer leaves much for the reader to infer from the data. The writer may have offered the data without the complete citation, which would allow the reader to determine the reliability of the data as evidence. The writer may offer data, which are not complete enough to allow the reader to determine their significance.	The supporting data are complete, accurate, and relevant to the claim.

Warrants

No rules and principles are offered.	The writer recognizes a need to connect the data to the claim and states some elaboration of data, but the writer fails to make the connection. Or most rules and principles are not valid or relevant.	The writer explains the data in some way, but the explanation is not linked specifically to the claim.	The writer explains the data in such a way that it is clear how they support the claim.

Backings

No sources of warrants are given.	The writer states incorrect, irrelevant sources of warrants.	The writer states correct, relevant sources of warrants but the sources are very general, not specific.	The writer states correct, relevant, and specific sources of warrants.

Rebuttals

No recognition of constraints of solutions.	The writer offers few constraints of solutions but the constraints are not elaborated.	The writer identifies constraints of solutions but the constraints are not sufficient.	The writer states complete and systematic identification of constraints of solutions.

How Do We Code Student Arguments?

When students are engaged in an argumentative discussion, either face to face or online, their arguments can also be assessed. If the discussion is face to face, it is necessary to transcribe the discussion in order to later assess it. When assessing online discussions, most bulletin-board software allows you to save each student's message as a separate record in a database. The messages that students posted that are stored in the database can be counted and qualitatively analyzed for which components of argumentation used are present in each posting. Cho and Jonassen (2002) analyzed student online discussion while solving problems by using a coding scheme adapted from Toulmin's (1968) model of argument (described before). Each message was classified by two coders into one of those five categories without knowing the identity of the group. After classifying all of the messages, we counted the number of each category used during the discussion. Analysis showed that students using an argumentation scaffold, Belvedere (described in Chapter 20), produced significantly more argument components during group discussions than subjects in the discussion groups that did not have access to the scaffold. Specifically, groups using the scaffold produced significantly more claims and grounds than groups who did not have access to the scaffold. The analysis also showed that groups solving ill-structured problems produced more arguments during group discussions than students solving well-structured problems, especially in stating rebuttals. Groups solving ill-structured tasks produced more rebuttals than those solving well-structured problems because this kind of reasoning is more important to that kind of problem solving.

How Do We Assess Mental Simulations (Solution Scenarios)?

In Chapters 3 and 6, I described the construction of mental simulations, also known as scenarios. Scenarios are hypothetical sequences of events constructed that may result from different decisions (Kahn, 1965). Policy analysts (see Chapter 6) construct scenarios when assessing long-range economic, political, and societal developments. For example, scenarios were used to inform important military and political decisions such as:

- Should the US invade Iraq to depose Saddam Hussein?
- Should we increase troop strength in Afghanistan?
- Should we grant marriage benefits to same-sex partners?

As indicated in Chapter 3, Truman predicted that unleashing an atomic weapon on Hiroshima would reduce the loss of lives overall, demoralize the Japanese, and strengthen America's hand after the war. Truman no doubt constructed such a scenario while making that horrific decision.

According to Kahn (1965), a scenario is:

- **hypothetical**, representing a possible future;
- **selective**, representing one possible state of complex, interdependent, and dynamic affairs;
- **bounded**, consisting of number of states, events, actions, and consequences;
- **connected** by causally related elements and events;
- **assessable**, providing a judgment based on probability.

Most scenarios are exploratory or anticipatory where the scenario constructor starts with some states and anticipates future consequences (making predictions), although some are normative, where scenarios describe futures as they should be. Scenarios present a chain of causally related events resulting from implementation of some option and leading to some outcome (Tversky & Kahneman, 1980). The network of causally related events in the scenario can take on various states depending on which actions are taken. Scenario generation is a kind of mental simulation of future events.

For purposes of designing problem-solving learning environments (PSLEs), scenario construction can be used to assess the ability to make meaningful decisions and predictions about their outcomes. Although unsupported by empirical research, I suggest that scenarios that are constructed by learners can be assessed using criteria, such as:

- all beginning factors, states, and conditions identified;

- assumptions about factors, states, and conditions supported by evidence;
- all predictions plausible (probable);
- predictions based on interdependent, dynamic relationships among changes in factors, states, and conditions;
- influences among factors supported by evidence;
- intermediate events, actions, and consequences plausible;
- interfering events, probabilities and impacts plausible;
- causal map (influence diagram) included.

How Do We Assess Students-Constructed Cases?

Strobel, Jonassen, and Ionas (2008) conducted a three-year, design-based research study on case-based learning. Beginning with a cognitive flexibility hypertext (see Chapter 13), they found that students slowly adapted to the nonlinear interconnections among the different content-types; however, students experienced difficulties in making comparisons, because the environments did not provide space for student construction of their own ideas. Flexibility hypertexts are static, providing a definitive body of material that is difficult for users to elaborate. Users of the system were unable to contribute their own perspectives, links, or connections, so they were passive consumers of information stored in the environment.

Therefore, in the second and third iterations, the system shifted from a content-navigation environment to a student-authoring environment, because authoring hypertext requires deeper understanding of the domain, identification of core concepts, cases, themes, and careful selection of new cases to represent the content (Jacobson & Archodidou, 2000). We incorporated authoring functions that gave students more control of the environment, so that the focus of designing the hypertext system shifts from content and relationship development to providing support structures and guidance to the end users as the instructional designer of their own learning experience. When students construct and elaborate their own cases, they are more deeply engaged in learning than when interpreting someone else's cases.

A potentially powerful, yet empirically unexamined form of problem-solving assessment is the construction of PSLEs by students. Student construction of problems is a transfer task. After engaging in problem-solving activities in instructor-provided PSLEs, we have informally investigated the construction of problems by students. Using simple web-construction tools, students construct their own problem situations and supports. Their environments may be assessed by asking questions such as:

- Are users required to solve a real problem?
- Are the problems authentic? Situated in meaningful context?
- Are supports appropriate for problem type?
- Are meaningful perspectives provided?
- Are analogous cases provided? Prior experiences?
- Do users have to articulate causal model of problem-solution?
- Are questions used to scaffold performance?
- Do users have to construct arguments in support of solution?

For instructors who have produced their own PSLEs to engage students in problem solving, an added advantage to requiring students to construct transfer problems is an increased library of PSLEs that may be used in future years to engage even more students in problem solving. That is the primary goal of this book.

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