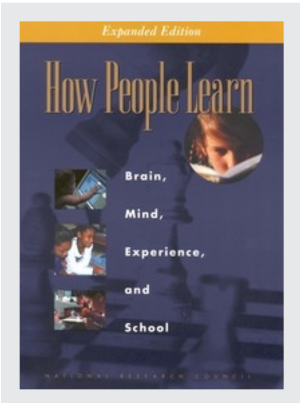

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Committee on Developments in the Science of Learning with additional material from the Committee on Learning Research and Educational Practice, National Research Council

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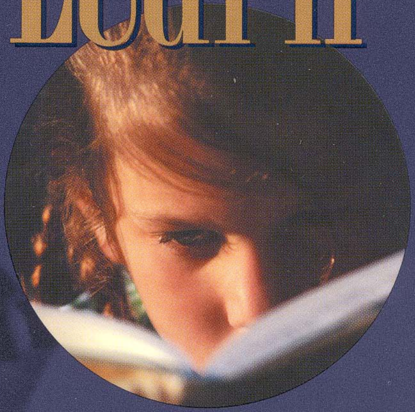

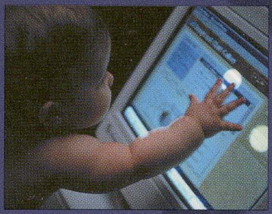

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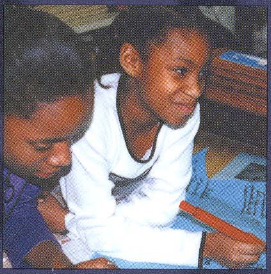

Experience,

and

School

NATIONAL RESEARCH COUNCIL

Expanded Edition

How People Learn

Brain, Mind, Experience, and School

Committee on Developments in the Science of Learning

John D. Bransford, Ann L. Brown, and Rodney R. Cocking, *editors*

with additional material from the

Committee on Learning Research and Educational Practice

M. Suzanne Donovan, John D. Bransford, and James W. Pellegrino, *editors*

Commission on Behavioral and Social Sciences and Education

National Research Council

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In Memory of
Ann L. Brown
(1943-1999)
Scholar and Scientist
Champion of Children and Those Who Teach Them
Whose Vision It Was to
Bring Learning Research
into the Classroom

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Preface

This expanded edition of *How People Learn* is the result of the work of two committees of the Commission on Behavioral and Social Sciences and Education of the National Research Council (NRC). The original volume, published in April 1999, was the product of a 2-year study conducted by the Committee on Developments in the Science of Learning. Following its publication, a second NRC committee, the Committee on Learning Research and Educational Practice, was formed to carry that volume an essential step further by exploring the critical issue of how better to link the findings of research on the science of learning to actual practice in the classroom. The results of that effort were captured in *How People Learn: Bridging Research and Practice*, published in June 1999. The present volume draws on that report to expand on the findings, conclusions, and research agenda presented in the original volume.

During the course of these efforts, a key contributor and one of the most eloquent voices on the importance of applying the science of learning to classroom practice was lost. The educational community mourns the death of Ann L. Brown, Graduate School of Education, University of California at Berkeley, cochair of the Committee on Developments in the Science of Learning and an editor of *How People Learn.* Her insight and dedication to improving education through science will be sorely missed.

John D. Bransford, *Cochair*
Committee on Developments in the Science of Learning
Committee on Learning Research and Educational Practice

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I

INTRODUCTION

1

Learning: From Speculation to Science

The essence of matter, the origins of the universe, the nature of the human mind—these are the profound questions that have engaged thinkers through the centuries. Until quite recently, understanding the mind—and the thinking and learning that the mind makes possible—has remained an elusive quest, in part because of a lack of powerful research tools. Today, the world is in the midst of an extraordinary outpouring of scientific work on the mind and brain, on the processes of thinking and learning, on the neural processes that occur during thought and learning, and on the development of competence.

The revolution in the study of the mind that has occurred in the last three or four decades has important implications for education. As we illustrate, a new theory of learning is coming into focus that leads to very different approaches to the design of curriculum, teaching, and assessment than those often found in schools today. Equally important, the growth of interdisciplinary inquiries and new kinds of scientific collaborations have begun to make the path from basic research to educational practice somewhat more visible, if not yet easy to travel. Thirty years ago, educators paid little attention to the work of cognitive scientists, and researchers in the nascent field of cognitive science worked far removed from classrooms. Today, cognitive researchers are spending more time working with teachers, testing and refining their theories in real classrooms where they can see how different settings and classroom interactions influence applications of their theories.

What is perhaps currently most striking is the variety of research approaches and techniques that have been developed and ways in which evidence from many different branches of science are beginning to converge. The story we can now tell about learning is far richer than ever before, and it promises to evolve dramatically in the next generation. For example:

- Research from cognitive psychology has increased understanding of the nature of competent performance and the principles of knowledge organization that underlie people's abilities to solve problems in a wide variety of areas, including mathematics, science, literature, social studies, and history.
- Developmental researchers have shown that young children understand a great deal about basic principles of biology and physical causality, about number, narrative, and personal intent, and that these capabilities make it possible to create innovative curricula that introduce important concepts for advanced reasoning at early ages.
- Research on learning and transfer has uncovered important principles for structuring learning experiences that enable people to use what they have learned in new settings.
- Work in social psychology, cognitive psychology, and anthropology is making clear that all learning takes place in settings that have particular sets of cultural and social norms and expectations and that these settings influence learning and transfer in powerful ways.
- Neuroscience is beginning to provide evidence for many principles of learning that have emerged from laboratory research, and it is showing how learning changes the physical structure of the brain and, with it, the functional organization of the brain.
- Collaborative studies of the design and evaluation of learning environments, among cognitive and developmental psychologists and educators, are yielding new knowledge about the nature of learning and teaching as it takes place in a variety of settings. In addition, researchers are discovering ways to learn from the "wisdom of practice" that comes from successful teachers who can share their expertise.
- Emerging technologies are leading to the development of many new opportunities to guide and enhance learning that were unimagined even a few years ago.

All of these developments in the study of learning have led to an era of new relevance of science to practice. In short, investment in basic research is paying off in practical applications. These developments in understanding of how humans learn have particular significance in light of changes in what is expected of the nation's educational systems.

In the early part of the twentieth century, education focused on the acquisition of literacy skills: simple reading, writing, and calculating. It was not the general rule for educational systems to train people to think and read critically, to express themselves clearly and persuasively, to solve complex problems in science and mathematics. Now, at the end of the century, these aspects of high literacy are required of almost everyone in order to successfully negotiate the complexities of contemporary life. The skill demands for work have increased dramatically, as has the need for organizations and workers to change in response to competitive workplace pressures. Thoughtful participation in the democratic process has also become increasingly complicated as the locus of attention has shifted from local to national and global concerns.

Above all, information and knowledge are growing at a far more rapid rate than ever before in the history of humankind. As Nobel laureate Herbert Simon wisely stated, the meaning of "knowing" has shifted from being able to remember and repeat information to being able to find and use it (Simon, 1996). More than ever, the sheer magnitude of human knowledge renders its coverage by education an impossibility; rather, the goal of education is better conceived as helping students develop the intellectual tools and learning strategies needed to acquire the knowledge that allows people to think productively about history, science and technology, social phenomena, mathematics, and the arts. Fundamental understanding about subjects, including how to frame and ask meaningful questions about various subject areas, contributes to individuals' more basic understanding of principles of learning that can assist them in becoming self-sustaining, lifelong learners.

FOCUS: PEOPLE, SCHOOLS, AND THE POTENTIAL TO LEARN

The scientific literatures on cognition, learning, development, culture, and brain are voluminous. Three organizing decisions, made fairly early in the work of the committee, provided the framework for our study and are reflected in the contents of this book.

- First, we focus primarily on research on human learning (though the study of animal learning provides important collateral information), including new developments from neuroscience.
- Second, we focus especially on learning research that has implications for the design of formal instructional environments, primarily preschools, kindergarten through high schools (K-12), and colleges.
- Third, and related to the second point, we focus on research that helps explore the possibility of helping all individuals achieve their fullest potential.

New ideas about ways to facilitate learning—and about who is most capable of learning—can powerfully affect the quality of people's lives. At different points in history, scholars have worried that formal educational environments have been better at selecting talent than developing it (see, e.g., Bloom, 1964). Many people who had difficulty in school might have prospered if the new ideas about effective instructional practices had been available. Furthermore, given new instructional practices, even those who did well in traditional educational environments might have developed skills, knowledge, and attitudes that would have significantly enhanced their achievements.

Learning research suggests that there are new ways to introduce students to traditional subjects, such as mathematics, science, history and literature, and that these new approaches make it possible for the majority of individuals to develop a deep understanding of important subject matter. This committee is especially interested in theories and data that are relevant to the development of new ways to introduce students to such traditional subjects as mathematics, science, history, and literature. There is hope that new approaches can make it possible for a majority of individuals to develop a moderate to deep understanding of important subjects.

DEVELOPMENT OF THE SCIENCE OF LEARNING

This report builds on research that began in the latter part of the nineteenth century—the time in history at which systematic attempts were made to study the human mind through scientific methods. Before then, such study was the province of philosophy and theology. Some of the most influential early work was done in Leipzig in the laboratory of Wilhelm Wundt, who with his colleagues tried to subject human consciousness to precise analysis—mainly by asking subjects to reflect on their thought processes through introspection.

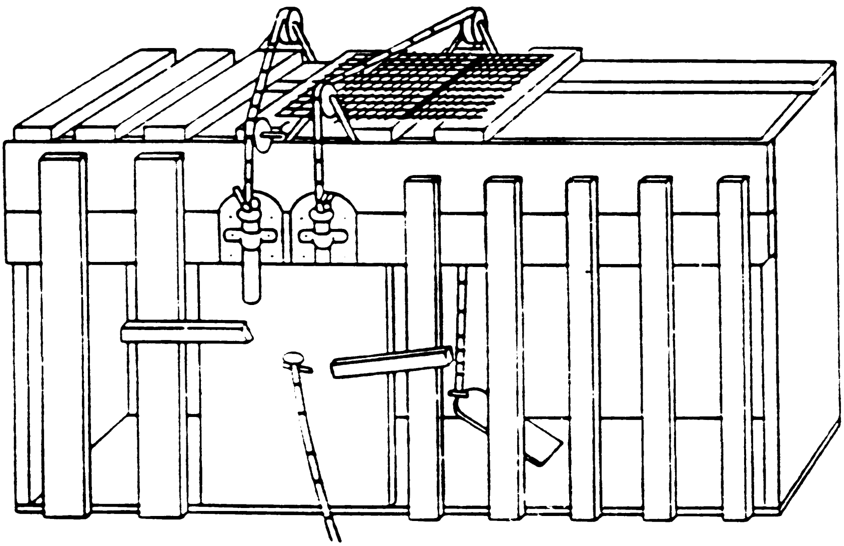
By the turn of the century, a new school of behaviorism was emerging. In reaction to the subjectivity inherent in introspection, behaviorists held that the scientific study of psychology must restrict itself to the study of observable behaviors and the stimulus conditions that control them. An extremely influential article, published by John B. Watson in 1913, provides a glimpse of the behaviorist credo:

> . . . all schools of psychology except that of behaviorism claim that "consciousness" is the subject-matter of psychology. Behaviorism, on the contrary, holds that the subject matter of human psychology is the behavior or activities of the human being. Behaviorism claims that "consciousness" is neither a definable nor a useable concept; that it is merely another word for the "soul" of more ancient times. The old psychology is thus dominated by a kind of subtle religious philosophy (p. 1).

Drawing on the empiricist tradition, behaviorists conceptualized learning as a process of forming connections between stimuli and responses. Motivation to learn was assumed to be driven primarily by drives, such as hunger, and the availability of external forces, such as rewards and punishments (e.g., Thorndike, 1913; Skinner, 1950).

In a classic behaviorist study by Edward L. Thorndike (1913), hungry cats had to learn to pull a string hanging in a "puzzle box" in order for a door to open that let them escape and get food. What was involved in learning to escape in this manner? Thorndike concluded that the cats did not think about how to escape and then do it; instead, they engaged in trial-and-error behavior; see Box 1.1. Sometimes a cat in the puzzle box accidentally pulled the strings while playing and the door opened, allowing the cat to escape. But this event did not appear to produce an insight on the part of

BOX 1.1 A Cat's Learning



"When put into the box, the cat would show evident signs of discomfort and impulse to escape from confinement. It tries to squeeze through any opening; it claws and bites at the wire; it thrusts its paws out through any opening and claws at everything it reaches. . . . It does not pay very much attention to the food outside but seems simply to strive instinctively to escape from confinement. . . . The cat that is clawing all over the box in her impulsive struggle will probably claw the string or loop or button so as to open the door. And gradually all the other unsuccessful impulses will be stamped out and the particular impulse leading to the successful act will be stamped in by the resulting pleasure, until, after many trials, the cat will, when put in the box, immediately claw the button or loop in a definite way" (Thorndike, 1913:13).

the cat because, when placed in the puzzle box again, the cat did not immediately pull the string to escape. Instead, it took a number of trials for the cats to learn through trial and error. Thorndike argued that rewards (e.g., food) increased the strength of connections between stimuli and responses. The explanation of what appeared to be complex problem-solving phenomena as escaping from a complicated puzzle box could thus be explained without recourse to unobservable mental events, such as thinking.

A limitation of early behaviorism stemmed from its focus on observable stimulus conditions and the behaviors associated with those conditions. This orientation made it difficult to study such phenomena as understanding, reasoning, and thinking—phenomena that are of paramount importance for education. Over time, radical behaviorism (often called "Behaviorism with a Capital B") gave way to a more moderate form of behaviorism ("behaviorism with a small b") that preserved the scientific rigor of using behavior as data, but also allowed hypotheses about internal "mental" states when these became necessary to explain various phenomena (e.g., Hull, 1943; Spence, 1942).

In the late 1950s, the complexity of understanding humans and their environments became increasingly apparent, and a new field emerged—cognitive science. From its inception, cognitive science approached learning from a multidisciplinary perspective that included anthropology, linguistics, philosophy, developmental psychology, computer science, neuroscience, and several branches of psychology (Norman, 1980,1993; Newell and Simon, 1972). New experimental tools, methodologies, and ways of postulating theories made it possible for scientists to begin serious study of mental functioning: to test their theories rather than simply speculate about thinking and learning (see, e.g., Anderson, 1982, 1987; deGroot, 1965,1969; Newell and Simon, 1972; Ericsson and Charness, 1994), and, in recent years, to develop insights into the importance of the social and cultural contexts of learning (e.g., Cole, 1996; Lave, 1988; Lave and Wenger, 1991; Rogoff, 1990; Rogoff et al., 1993). The introduction of rigorous qualitative research methodologies have provided perspectives on learning that complement and enrich the experimental research traditions (Erickson, 1986; Hammersly and Atkinson, 1983; Heath, 1982; Lincoln and Guba, 1985; Marshall and Rossman, 1955; Miles and Huberman, 1984; Spradley, 1979).

Learning with Understanding

One of the hallmarks of the new science of learning is its emphasis on learning with understanding. Intuitively, understanding is good, but it has been difficult to study from a scientific perspective. At the same time, students often have limited opportunities to understand or make sense of topics because many curricula have emphasized memory rather than understanding. Textbooks are filled with facts that students are expected to memorize, and most tests assess students' abilities to remember the facts. When studying about veins and arteries, for example, students may be expected to remember that arteries are thicker than veins, more elastic, and carry blood from the heart; veins carry blood back to the heart. A test item for this information may look like the following:

1. Arteries
   a. Are more elastic than veins
   b. Carry blood that is pumped from the heart
   c. Are less elastic than veins
   d. Both a and b
   e. Both b and c

The new science of learning does not deny that facts are important for thinking and problem solving. Research on expertise in areas such as chess, history, science, and mathematics demonstrate that experts' abilities to think and solve problems depend strongly on a rich body of knowledge about subject matter (e.g., Chase and Simon, 1973; Chi et al., 1981; deGroot, 1965). However, the research also shows clearly that "usable knowledge" is not the same as a mere list of disconnected facts. Experts' knowledge is connected and organized around important concepts (e.g., Newton's second law of motion); it is "conditionalized" to specify the contexts in which it is applicable; it supports understanding and transfer (to other contexts) rather than only the ability to remember.

For example, people who are knowledgeable about veins and arteries know more than the facts noted above: they also understand why veins and arteries have particular properties. They know that blood pumped from the heart exits in spurts and that the elasticity of the arteries helps accommodate pressure changes. They know that blood from the heart needs to move upward (to the brain) as well as downward and that the elasticity of an artery permits it to function as a one-way valve that closes at the end of each spurt and prevents the blood from flowing backward. Because they understand relationships between the structure and function of veins and arteries, knowledgeable individuals are more likely to be able to use what they have learned to solve novel problems—to show evidence of transfer. For example, imagine being asked to design an artificial artery—would it have to be elastic? Why or why not? An understanding of reasons for the properties of arteries suggests that elasticity may not be necessary—perhaps the problem can be solved by creating a conduit that is strong enough to handle the pressure of spurts from the heart and also function as a one-way valve. An understanding of veins and arteries does not guarantee an answer to this design question, but it does support thinking about alternatives that are not readily available if one only memorizes facts (Bransford and Stein, 1993).

Pre-Existing Knowledge

An emphasis on understanding leads to one of the primary characteristics of the new science of learning: its focus on the processes of knowing (e.g., Piaget, 1978; Vygotsky, 1978). Humans are viewed as goal-directed agents who actively seek information. They come to formal education with a range of prior knowledge, skills, beliefs, and concepts that significantly influence what they notice about the environment and how they organize and interpret it. This, in turn, affects their abilities to remember, reason, solve problems, and acquire new knowledge.

Even young infants are active learners who bring a point of view to the learning setting. The world they enter is not a "booming, buzzing confusion" (James, 1890), where every stimulus is equally salient. Instead, an infant's brain gives precedence to certain kinds of information: language, basic concepts of number, physical properties, and the movement of animate and inanimate objects. In the most general sense, the contemporary view of learning is that people construct new knowledge and understandings based on what they already know and believe (e.g., Cobb, 1994; Piaget, 1952, 1973a,b, 1977, 1978; Vygotsky, 1962, 1978). A classic children's book illustrates this point; see Box 1.2.

A logical extension of the view that new knowledge must be constructed from existing knowledge is that teachers need to pay attention to the incomplete understandings, the false beliefs, and the naive renditions of concepts that learners bring with them to a given subject. Teachers then need to build on these ideas in ways that help each student achieve a more mature understanding. If students' initial ideas and beliefs are ignored, the understandings that they develop can be very different from what the teacher intends.

Consider the challenge of working with children who believe that the earth is flat and attempting to help them understand that it is spherical. When told it is round, children picture the earth as a pancake rather than as a sphere (Vosniadou and Brewer, 1989). If they are then told that it is round like a sphere, they interpret the new information about a spherical earth within their flat-earth view by picturing a pancake-like flat surface inside or on top of a sphere, with humans standing on top of the pancake. The children's construction of their new understandings has been guided by a model of the earth that helped them explain how they could stand or walk upon its surface, and a spherical earth did not fit their mental model. Like *Fish Is Fish*, everything the children heard was incorporated into that pre-existing view.

Fish Is Fish is relevant not only for young children, but for learners of all ages. For example, college students often have developed beliefs about physical and biological phenomena that fit their experiences but do not fit scientific accounts of these phenomena. These preconceptions must be

BOX 1.2 *Fish Is Fish*

Fish Is Fish (Lionni, 1970) describes a fish who is keenly interested in learning about what happens on land, but the fish cannot explore land because it can only breathe in water. It befriends a tadpole who grows into a frog and eventually goes out onto the land. The frog returns to the pond a few weeks later and reports on what he has seen. The frog describes all kinds of things like birds, cows, and people. The book shows pictures of the fish's representations of each of these descriptions: each is a fish-like form that is slightly adapted to accommodate the frog's descriptions—people are imagined to be fish who walk on their tailfins, birds are fish with wings, cows are fish with udders. This tale illustrates both the creative opportunities and dangers inherent in the fact that people construct new knowledge based on their current knowledge.

addressed in order for them to change their beliefs (e.g., Confrey, 1990; Mestre, 1994; Minstrell, 1989; Redish, 1996).

A common misconception regarding "constructivist" theories of knowing (that existing knowledge is used to build new knowledge) is that teachers should never tell students anything directly but, instead, should always allow them to construct knowledge for themselves. This perspective confuses a theory of pedagogy (teaching) with a theory of knowing. Constructivists assume that all knowledge is constructed from previous knowledge, irrespective of how one is taught (e.g., Cobb, 1994)—even listening to a lecture involves active attempts to construct new knowledge. *Fish Is Fish* (Lionni, 1970) and attempts to teach children that the earth is round (Vosniadou and Brewer, 1989) show why simply providing lectures frequently does not work. Nevertheless, there are times, usually after people have first grappled with issues on their own, that "teaching by telling" can work extremely well (e.g., Schwartz and Bransford, 1998). However, teachers still need to pay attention to students' interpretations and provide guidance when necessary.

There is a good deal of evidence that learning is enhanced when teachers pay attention to the knowledge and beliefs that learners bring to a learning task, use this knowledge as a starting point for new instruction, and monitor students' changing conceptions as instruction proceeds. For example, sixth graders in a suburban school who were given inquiry-based physics instruction were shown to do better on conceptual physics problems than eleventh and twelfth grade physics students taught by conventional methods in the same school system. A second study comparing seventh-ninth grade urban students with the eleventh and twelfth grade suburban physics students again showed that the younger students, taught by the inquiry-based approach, had a better grasp of the fundamental principles of physics (White and Frederickson, 1997, 1998). New curricula for young children have also demonstrated results that are extremely promising: for example, a new approach to teaching geometry helped second-grade children learn to represent and visualize three-dimensional forms in ways that exceeded the skills of a comparison group of undergraduate students at a leading university (Lehrer and Chazan, 1998). Similarly, young children have been taught to demonstrate powerful forms of early geometry generalizations (Lehrer and Chazan, 1998) and generalizations about science (Schauble et al., 1995; Warren and Rosebery, 1996).

Active Learning

New developments in the science of learning also emphasize the importance of helping people take control of their own learning. Since understanding is viewed as important, people must learn to recognize when they understand and when they need more information. What strategies might they use to assess whether they understand someone else's meaning? What kinds of evidence do they need in order to believe particular claims? How can they build their own theories of phenomena and test them effectively?

Many important activities that support active learning have been studied under the heading of "metacognition," a topic discussed in more detail in Chapters 2 and 3. Metacognition refers to people's abilities to predict their performances on various tasks (e.g., how well they will be able to remember various stimuli) and to monitor their current levels of mastery and understanding (e.g., Brown, 1975; Flavell, 1973). Teaching practices congruent with a metacognitive approach to learning include those that focus on sense-making, self-assessment, and reflection on what worked and what needs improving. These practices have been shown to increase the degree to which students transfer their learning to new settings and events (e.g., Palincsar and Brown, 1984; Scardamalia et al., 1984; Schoenfeld, 1983, 1985, 1991).

Imagine three teachers whose practices affect whether students learn to take control of their own learning (Scardamalia and Bereiter, 1991). Teacher A's goal is to get the students to produce work; this is accomplished by supervising and overseeing the quantity and quality of the work done by the students. The focus is on activities, which could be anything from old-style workbook activities to the trendiest of space-age projects. Teacher B assumes responsibility for what the students are learning as they carry out their activities. Teacher C does this as well, but with the added objective of continually turning more of the learning process over to the students. Walking into a classroom, you cannot immediately tell these three kinds of teachers apart. One of the things you might see is the students working in groups to produce videos or multimedia presentations. The teacher is likely to be found going from group to group, checking how things are going and responding to requests. Over the course of a few days, however, differences between Teacher A and Teacher B would become evident. Teacher A's focus is entirely on the production process and its products—whether the students are engaged, whether everyone is getting fair treatment, and whether they are turning out good pieces of work. Teacher B attends to all of this as well, but Teacher B is also attending to what the students are learning from the experience and is taking steps to ensure that the students are processing content and not just dealing with show. To see a difference between Teachers B and C, however, you might need to go back into the history of the media production project. What brought it about in the first place? Was it conceived from the start as a learning activity, or did it emerge from the students' own knowledge building efforts? In one striking example of a Teacher C classroom, the students had been studying cockroaches and had learned so much from their reading and observation that they wanted to share it with the rest of the school; the production of a video came about to achieve that purpose (Lamon et al., 1997).

The differences in what might seem to be the same learning activity are thus quite profound. In Teacher A's classroom, the students are learning something of media production, but the media production may very well be getting in the way of learning anything else. In Teacher B's classroom, the teacher is working to ensure that the original educational purposes of the activity are met, that it does not deteriorate into a mere media production exercise. In Teacher C's classroom, the media production is continuous with and a direct outgrowth of the learning that is embodied in the media production. The greater part of Teacher C's work has been done before the idea of a media production even comes up, and it remains only to help the students keep sight of their purposes as they carry out the project.

These hypothetical teachers—A, B, and C—are abstract models that of course fit real teachers only partly, and more on some days than others. Nevertheless, they provide important glimpses of connections between goals for learning and teaching practices that can affect students' abilities to accomplish these goals.

Implications for Education

Overall, the new science of learning is beginning to provide knowledge to improve significantly people's abilities to become active learners who seek to understand complex subject matter and are better prepared to transfer what they have learned to new problems and settings. Making this happen is a major challenge (e.g., Elmore et al., 1996), but it is not impossible. The emerging science of learning underscores the importance of rethinking what is taught, how it is taught, and how learning is assessed. These ideas are developed throughout this volume.

An Evolving Science

This volume synthesizes the scientific basis of learning. The scientific achievements include a fuller understanding of: (1) memory and the structure of knowledge; (2) problem solving and reasoning; (3) the early foundations of learning; (4) regulatory processes that govern learning, including metacognition; and (5) how symbolic thinking emerges from the culture and community of the learner.

These key characteristics of learned proficiency by no means plumb the depths of human cognition and learning. What has been learned about the principles that guide some aspects of learning do not constitute a complete picture of the principles that govern all domains of learning. The scientific bases, while not superficial in themselves, do represent only a surface level of a complete understanding of the subject. Only a few domains of learning have been examined in depth, as reflected in this book, and new, emergent areas, such as interactive technologies (Greenfield and Cocking, 1996) are challenging generalizations from older research studies.

As scientists continue to study learning, new research procedures and methodologies are emerging that are likely to alter current theoretical conceptions of learning, such as computational modeling research. The scientific work encompasses a broad range of cognitive and neuroscience issues in learning, memory, language, and cognitive development. Studies of parallel distributed processing, for example (McClelland et al., 1995; Plaut et al., 1996; Munakata et al., 1997; McClelland and Chappell, 1998) look at learning as occurring through the adaptation of connections among participating neurons. The research is designed to develop explicit computational models to refine and extend basic principles, as well as to apply the models to substantive research questions through behavioral experiments, computer simulations, functional brain imaging, and mathematical analyses. These studies are thus contributing to modification of both theory and practice. New models also encompass learning in adulthood to add an important dimension to the scientific knowledge base.

Key Findings

This volume provides a broad overview of research on learners and learning and on teachers and teaching. Three findings are highlighted here because they have both a solid research base to support them and strong implications for how we teach.

1. Students come to the classroom with preconceptions about how the world works. If their initial understanding is not engaged, they may fail to grasp the new concepts and information that are

taught, or they may learn them for purposes of a test but revert to their preconceptions outside the classroom.

Research on early learning suggests that the process of making sense of the world begins at a very young age. Children begin in preschool years to develop sophisticated understandings (whether accurate or not) of the phenomena around them (Wellman, 1990). Those initial understandings can have a powerful effect on the integration of new concepts and information. Sometimes those understandings are accurate, providing a foundation for building new knowledge. But sometimes they are inaccurate (Carey and Gelman, 1991). In science, students often have misconceptions of physical properties that cannot be easily observed. In humanities, their preconceptions often include stereotypes or simplifications, as when history is understood as a struggle between good guys and bad guys (Gardner, 1991). A critical feature of effective teaching is that it elicits from students their preexisting understanding of the subject matter to be taught and provides opportunities to build on—or challenge—the initial understanding. James Minstrell, a high school physics teacher, describes the process as follows (Minstrell, 1989: 130-131):

> Students' initial ideas about mechanics are like strands of yarn, some unconnected, some loosely interwoven. The act of instruction can be viewed as helping the students unravel individual strands of belief, label them, and then weave them into a fabric of more complete understanding. Rather than denying the relevancy of a belief, teachers might do better by helping students differentiate their present ideas from and integrate them into conceptual beliefs more like those of scientists.

The understandings that children bring to the classroom can already be quite powerful in the early grades. For example, some children have been found to hold onto their preconception of a flat earth by imagining a round earth to be shaped like a pancake (Vosniadou and Brewer, 1989). This construction of a new understanding is guided by a model of the earth that helps the child explain how people can stand or walk on its surface. Many young children have trouble giving up the notion that one-eighth is greater than one-fourth, because 8 is more than 4 (Gelman and Gallistel, 1978). If children were blank slates, telling them that the earth is round or that one-fourth is greater than one-eighth would be adequate. But since they already have ideas about the earth and about numbers, those ideas must be directly addressed in order to transform or expand them.

Drawing out and working with existing understandings is important for learners of all ages. Numerous research experiments demonstrate the persistence of preexisting understandings among older students even after a new model has been taught that contradicts the naïve understanding. For example, in a study of physics students from elite, technologically oriented colleges, Andrea DiSessa (1982) instructed them to play a computerized game that required them to direct a computer-simulated object called a dynaturtle so that it would hit a target and do so with minimum speed at impact. Participants were introduced to the game and given a hands-on trial that allowed them to apply a few taps with a small wooden mallet to a tennis ball on a table before beginning the game. The same game was also played by elementary schoolchildren. DiSessa found that both groups of students failed dismally. Success would have required demonstrating an understanding of Newton's laws of motion. Despite their training, college physics students, like the elementary schoolchildren, aimed the moving dynaturtle directly at the target, failing to take momentum into account. Further investigation of one college student who participated in the study revealed that she knew the relevant physical properties and formulas, yet, in the context of the game, she fell back on her untrained conception of how the physical world works.

Students at a variety of ages persist in their beliefs that seasons are caused by the earth's distance from the sun rather than by the tilt of the earth (Harvard-Smithsonian Center for Astrophysics, 1987), or that an object that had been tossed in the air has both the force of gravity and the force of the hand that tossed it acting on it, despite training to the contrary (Clement, 1982). For the scientific understanding to replace the naïve understanding, students must reveal the latter and have the opportunity to see where it falls short.

2. To develop competence in an area of inquiry, students must: (a) have a deep foundation of factual knowledge, (b) understand facts and ideas in the context of a conceptual framework, and (c) organize knowledge in ways that facilitate retrieval and application.

This principle emerges from research that compares the performance of experts and novices and from research on learning and transfer. Experts, regardless of the field, always draw on a richly structured information base; they are not just "good thinkers" or "smart people." The ability to plan a task, to notice patterns, to generate reasonable arguments and explanations, and to draw analogies to other problems are all more closely intertwined with factual knowledge than was once believed.

But knowledge of a large set of disconnected facts is not sufficient. To develop competence in an area of inquiry, students must have opportunities to learn with understanding. Deep understanding of subject matter transforms factual information into usable knowledge. A pronounced difference between experts and novices is that experts' command of concepts shapes their understanding of new information: it allows them to see patterns, relationships, or discrepancies that are not apparent to novices. They do not necessarily have better overall memories than other people. But their conceptual understanding allows them to extract a level of meaning from information that is not apparent to novices, and this helps them select and remember relevant information. Experts are also able to fluently access relevant knowledge because their understanding of subject matter allows them to quickly identify what is relevant. Hence, their attention is not overtaxed by complex events.

In most areas of study in K-12 education, students will begin as novices; they will have informal ideas about the subject of study, and will vary in the amount of information they have acquired. The enterprise of education can be viewed as moving students in the direction of more formal understanding (or greater expertise). This will require both a deepening of the information base and the development of a conceptual framework for that subject matter.

Geography can be used to illustrate the manner in which expertise is organized around principles that support understanding. A student can learn to fill in a map by memorizing states, cities, countries, etc., and can complete the task with a high level of accuracy. But if the boundaries are removed, the problem becomes much more difficult. There are no concepts supporting the student's information. An expert who understands that borders often developed because natural phenomena (like mountains or water bodies) separated people, and that large cities often arose in locations that allowed for trade (along rivers, large lakes, and at coastal ports) will easily outperform the novice. The more developed the conceptual understanding of the needs of cities and the resource base that drew people to them, the more meaningful the map becomes. Students can become more expert if the geographical information they are taught is placed in the appropriate conceptual framework.

A key finding in the learning and transfer literature is that organizing information into a conceptual framework allows for greater "transfer"; that is, it allows the student to apply what was learned in new situations and to learn related information more quickly (see Box 1.3). The student who has learned geographical information for the Americas in a conceptual framework approaches the task of learning the geography of another part of the globe with questions, ideas, and expectations that help guide acquisition of the new information. Understanding the geographical importance of the Mississippi River sets the stage for the student's understanding of the geographical importance of the Nile. And as concepts are reinforced, the student will transfer learning beyond the classroom, observing and inquiring, for example, about the geographic features of a visited city that help explain its location and size (Holyoak, 1984; Novick and Holyoak, 1991).

3. A "metacognitive" approach to instruction can help students learn to take control of their own learning by defining learning goals and monitoring their progress in achieving them.

In research with experts who were asked to verbalize their thinking as they worked, it was revealed that they monitored their own understanding carefully, making note of when additional information was required for understanding, whether new information was consistent with what they already knew, and what analogies could be drawn that would advance their understanding. These meta-cognitive monitoring activities are an important component of what is called adaptive expertise (Hatano and Inagaki, 1986).

Because metacognition often takes the form of an internal conversation, it can easily be assumed that individuals will develop the internal dialogue on their own. Yet many of the strategies we use for thinking reflect cultural norms and methods of inquiry (Hutchins, 1995; Brice-Heath, 1981, 1983; Suina and Smolkin, 1994). Research has demonstrated that children can be taught these strategies, including the ability to predict outcomes, explain to oneself in order to improve understanding, note failures to comprehend, activate background knowledge, plan ahead, and apportion time and memory. Reciprocal teaching, for example, is a technique designed to improve students' reading comprehension by helping them explicate, elaborate, and monitor their understanding as they read (Palincsar and Brown, 1984). The model for using the meta-cognitive strategies is provided initially by the

BOX 1.3 Throwing Darts Under Water

In one of the most famous early studies comparing the effects of learning a procedure with learning with understanding, two groups of children practiced throwing darts at a target under water (described in Judd, 1908; see a conceptual replication by Hendrickson and Schroeder, 1941). One group received an explanation of the refraction of light, which causes the apparent location of the target to be deceptive. The other group only practiced dart throwing, without the explanation. Both groups did equally well on the practice task, which involved a target 12 inches under water. But the group that had been instructed about the abstract principle did much better when they had to transfer to a situation in which the target was under only 4 inches of water. Because they understood what they were doing, the group that had received instruction about the refraction of light could adjust their behavior to the new task.

teacher, and students practice and discuss the strategies as they learn to use them. Ultimately, students are able to prompt themselves and monitor their own comprehension without teacher support.

The teaching of metacognitive activities must be incorporated into the subject matter that students are learning (White and Frederickson, 1998). These strategies are not generic across subjects, and attempts to teach them as generic can lead to failure to transfer. Teaching metacognitive strategies in context has been shown to improve understanding in physics (White and Frederickson, 1998), written composition (Scardamalia et al., 1984), and heuristic methods for mathematical problem solving (Schoenfeld, 1983, 1984, 1991). And metacognitive practices have been shown to increase the degree to which students transfer to new settings and events (Lin and Lehman, in press; Palincsar and Brown, 1984; Scardamalia et al., 1984; Schoenfeld, 1983, 1984, 1991).

Each of these techniques shares a strategy of teaching and modeling the process of generating alternative approaches (to developing an idea in writing or a strategy for problem solving in mathematics), evaluating their merits in helping to attain a goal, and monitoring progress toward that goal. Class discussions are used to support skill development, with a goal of independence and self-regulation.

Implications for Teaching

The three core learning principles described above, simple though they seem, have profound implications for the enterprise of teaching and teacher preparation.

1. ***Teachers must draw out and work with the preexisting understandings that their students bring with them.*** This requires that:

- The model of the child as an empty vessel to be filled with knowledge provided by the teacher must be replaced. Instead, the teacher must actively inquire into students' thinking, creating classroom tasks and conditions under which student thinking can be revealed. Students' initial conceptions then provide the foundation on which the more formal understanding of the subject matter is built.
- The roles for assessment must be expanded beyond the traditional concept of testing. The use of frequent formative assessment helps make students' thinking visible to themselves, their peers, and their teacher. This provides feedback that can guide modification and refinement in thinking. Given the goal of learning with understanding, assessments must tap understanding rather than merely the ability to repeat facts or perform isolated skills.

• Schools of education must provide beginning teachers with opportunities to learn: (a) to recognize predictable preconceptions of students that make the mastery of particular subject matter challenging, (b) to draw out preconceptions that are not predictable, and (c) to work with preconceptions so that children build on them, challenge them and, when appropriate, replace them.

2. *Teachers must teach some subject matter in depth, providing many examples in which the same concept is at work and providing a firm foundation of factual knowledge.* This requires that:

• Superficial coverage of all topics in a subject area must be replaced with in-depth coverage of fewer topics that allows key concepts in that discipline to be understood. The goal of coverage need not be abandoned entirely, of course. But there must be a sufficient number of cases of in-depth study to allow students to grasp the defining concepts in specific domains within a discipline. Moreover, in-depth study in a domain often requires that ideas be carried beyond a single school year before students can make the transition from informal to formal ideas. This will require active coordination of the curriculum across school years.

• Teachers must come to teaching with the experience of in-depth study of the subject area themselves. Before a teacher can develop powerful pedagogical tools, he or she must be familiar with the progress of inquiry and the terms of discourse in the discipline, as well as understand the relationship between information and the concepts that help organize that information in the discipline. But equally important, the teacher must have a grasp of the growth and development of students' thinking about these concepts. The latter will be essential to developing teaching expertise, but not expertise in the discipline. It may therefore require courses, or course supplements, that are designed specifically for teachers.

• Assessment for purposes of accountability (e.g., statewide assessments) must test deep understanding rather than surface knowledge. Assessment tools are often the standard by which teachers are held accountable. A teacher is put in a bind if she or he is asked to teach for deep conceptual understanding, but in doing so produces students who perform more poorly on standardized tests. Unless new assessment tools are aligned with new approaches to teaching, the latter are unlikely to muster support among the schools and their constituent parents. This goal is as important as it is difficult to achieve. The format of standardized tests can encourage measurement of factual knowledge rather than conceptual understanding, but it also facilitates objective scoring. Measuring depth of understanding can pose challenges for objectivity. Much work needs to be done to minimize the trade-off between assessing depth and assessing objectively.

3. *The teaching of metacognitive skills should be integrated into the curriculum in a variety of subject areas.* Because metacognition often takes the form of an internal dialogue, many students may be unaware of its importance unless the processes are explicitly emphasized by teachers. An emphasis on metacognition needs to accompany instruction in each of the disciplines, because the type of monitoring required will vary. In history, for example, the student might be asking himself, "who wrote this document, and how does that affect the interpretation of events," whereas in physics the student might be monitoring her understanding of the underlying physical principle at work.

- Integration of metacognitive instruction with discipline-based learning can enhance student achievement and develop in students the ability to learn independently. It should be consciously incorporated into curricula across disciplines and age levels.
- Developing strong metacognitive strategies and learning to teach those strategies in a classroom environment should be standard features of the curriculum in schools of education.

Evidence from research indicates that when these three principles are incorporated into teaching, student achievement improves. For example, the Thinker Tools Curriculum for teaching physics in an interactive computer environment focuses on fundamental physical concepts and properties, allowing students to test their preconceptions in model building and experimentation activities. The program includes an "inquiry cycle" that helps students monitor where they are in the inquiry process. The program asks for students' reflective assessments and allows them to review the assessments of their fellow students. In one study, sixth graders in a suburban school who were taught physics using Thinker Tools performed better at solving conceptual physics problems than did eleventh and twelfth grade physics students in the same school system taught by conventional methods. A second study comparing urban students in grades 7 to 9 with suburban students in grades 11 and 12 again showed that the younger students taught by the inquiry-based approach had a superior grasp of the fundamental principles of physics (White and Frederickson, 1997, 1998).

Bringing Order to Chaos

A benefit of focusing on how people learn is that it helps bring order to a seeming cacophony of choices. Consider the many possible teaching strategies that are debated in education circles and the media. Figure 1.1 depicts them in diagram format: lecture-based teaching, text-based teaching, inquiry-based teaching, technology-enhanced teaching, teaching organized

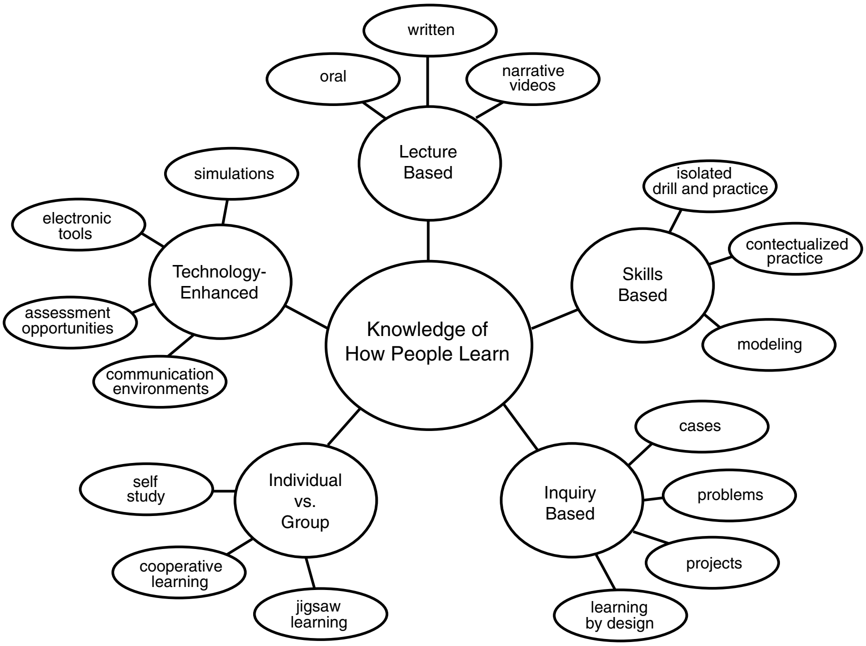


FIGURE 1.1 *With knowledge of how people learn, teachers can choose more purposefully among techniques to accomplish specific goals.*

around individuals versus cooperative groups, and so forth. Are some of these teaching techniques better than others? Is lecturing a poor way to teach, as many seem to claim? Is cooperative learning effective? Do attempts to use computers (technology-enhanced teaching) help achievement or hurt it?

This volume suggests that these are the wrong questions. Asking which teaching technique is best is analogous to asking which tool is best—a hammer, a screwdriver, a knife, or pliers. In teaching as in carpentry, the selection of tools depends on the task at hand and the materials one is working with. Books and lectures *can* be wonderfully efficient modes of transmitting new information for learning, exciting the imagination, and honing students' critical faculties—but one would choose other kinds of activities to elicit from students their preconceptions and level of understanding, or to help them see the power of using meta-cognitive strategies to monitor their learning. Hands-on experiments *can* be a powerful way to ground emergent knowledge, but they do not alone evoke the underlying conceptual understandings that aid generalization. There is no universal best teaching practice.

If, instead, the point of departure is a core set of learning principles, then the selection of teaching strategies (mediated, of course, by subject matter, grade level, and desired outcome) can be purposeful. The many possibilities then become a rich set of opportunities from which a teacher constructs an instructional program rather than a chaos of competing alternatives.

Focusing on how people learn also will help teachers move beyond either-or dichotomies that have plagued the field of education. One such issue is whether schools should emphasize "the basics" or teach thinking and problem-solving skills. This volume shows that both are necessary. Students' abilities to acquire organized sets of facts and skills are actually enhanced when they are connected to meaningful problem-solving activities, and when students are helped to understand why, when, and how those facts and skills are relevant. And attempts to teach thinking skills without a strong base of factual knowledge do not promote problem-solving ability or support transfer to new situations.

Designing Classroom Environments

Chapter 6 of this volume proposes a framework to help guide the design and evaluation of environments that can optimize learning. Drawing heavily on the three principles discussed above, it posits four interrelated attributes of learning environments that need cultivation.

1. ***Schools and classrooms must be learner centered.*** Teachers must pay close attention to the knowledge, skills, and attitudes that learners bring into the classroom. This incorporates the preconceptions regarding subject matter already discussed, but it also includes a broader understanding of the learner. For example:

- Cultural differences can affect students' comfort level in working collaboratively versus individually, and they are reflected in the background knowledge students bring to a new learning situation (Moll et al., 1993).
- Students' theories of what it means to be intelligent can affect their performance. Research shows that students who think that intelligence is a fixed entity are more likely to be performance oriented than learning oriented—they want to look good rather than risk making mistakes while learning. These students are especially likely to bail out when tasks become difficult. In contrast, students who think that intelligence is malleable are more willing to struggle with challenging tasks; they are more comfortable with risk (Dweck, 1989; Dweck and Legget, 1988).

Teachers in learner-centered classrooms also pay close attention to the individual progress of each student and devise tasks that are appropriate.

Learner-centered teachers present students with "just manageable difficulties"—that is, challenging enough to maintain engagement, but not so difficult as to lead to discouragement. They must therefore have an understanding of their students' knowledge, skill levels, and interests (Duckworth, 1987).

2. ***To provide a knowledge-centered classroom environment, attention must be given to what is taught (information, subject matter), why it is taught (understanding), and what competence or mastery looks like***. As mentioned above, research discussed in the following chapters shows clearly that expertise involves well-organized knowledge that supports understanding, and that learning with understanding is important for the development of expertise because it makes new learning easier (i.e., supports transfer).

Learning with understanding is often harder to accomplish than simply memorizing, and it takes more time. Many curricula fail to support learning with understanding because they present too many disconnected facts in too short a time—the "mile wide, inch deep" problem. Tests often reinforce memorizing rather than understanding. The knowledge-centered environment provides the necessary depth of study, assessing student understanding rather than factual memory. It incorporates the teaching of meta-cognitive strategies that further facilitate future learning.

Knowledge-centered environments also look beyond engagement as the primary index of successful teaching (Prawaf et al., 1992). Students' interest or engagement in a task is clearly important. Nevertheless, it does not guarantee that students will acquire the kinds of knowledge that will support new learning. There are important differences between tasks and projects that encourage hands-on doing and those that encourage doing with understanding; the knowledge-centered environment emphasizes the latter (Greeno, 1991).

3. ***Formative assessments—ongoing assessments designed to make students' thinking visible to both teachers and students—are essential. They permit the teacher to grasp the students' preconceptions, understand where the students are in the "developmental corridor" from informal to formal thinking, and design instruction accordingly. In the assessment-centered classroom environment, formative assessments help both teachers and students monitor progress.***

An important feature of assessments in these classrooms is that they be learner-friendly: they are not the Friday quiz for which information is memorized the night before, and for which the student is given a grade that ranks him or her with respect to classmates. Rather, these assessments should provide students with opportunities to revise and improve their thinking (Vye et al., 1998b), help students see their own progress over the course of weeks or months, and help teachers identify problems that need to be remedied (problems that may not be visible without the assessments). For example, a high school class studying the principles of democracy might be given a scenario in which a colony of people have just settled on the moon and must establish a government. Proposals from students of the defining features of such a government, as well as discussion of the problems they foresee in its establishment, can reveal to both teachers and students areas in which student thinking is more and less advanced. The exercise is less a test than an indicator of where inquiry and instruction should focus.

4. ***Learning is influenced in fundamental ways by the context in which it takes place. A community-centered approach requires the development of norms for the classroom and school, as well as connections to the outside world, that support core learning values.***

The norms established in the classroom have strong effects on students' achievement. In some schools, the norms could be expressed as "don't get caught not knowing something." Others encourage academic risk-taking and opportunities to make mistakes, obtain feedback, and revise. Clearly, if students are to reveal their preconceptions about a subject matter, their questions, and their progress toward understanding, the norms of the school must support their doing so.

Teachers must attend to designing classroom activities and helping students organize their work in ways that promote the kind of intellectual camaraderie and the attitudes toward learning that build a sense of community. In such a community, students might help one another solve problems by building on each other's knowledge, asking questions to clarify explanations, and suggesting avenues that would move the group toward its goal (Brown and Campione, 1994). Both cooperation in problem solving (Evans, 1989; Newstead and Evans, 1995) and argumentation (Goldman, 1994; Habermas, 1990; Kuhn, 1991; Moshman, 1995a, 1995b; Salmon and Zeitz, 1995; Youniss and Damon, 1992) among students in such an intellectual community enhance cognitive development.

Teachers must be enabled and encouraged to establish a community of learners among themselves (Lave and Wegner, 1991). These communities can build a sense of comfort with questioning rather than knowing the answer and can develop a model of creating new ideas that build on the contributions of individual members. They can engender a sense of the excitement of learning that is then transferred to the classroom, conferring a sense of ownership of new ideas as they apply to theory and practice.

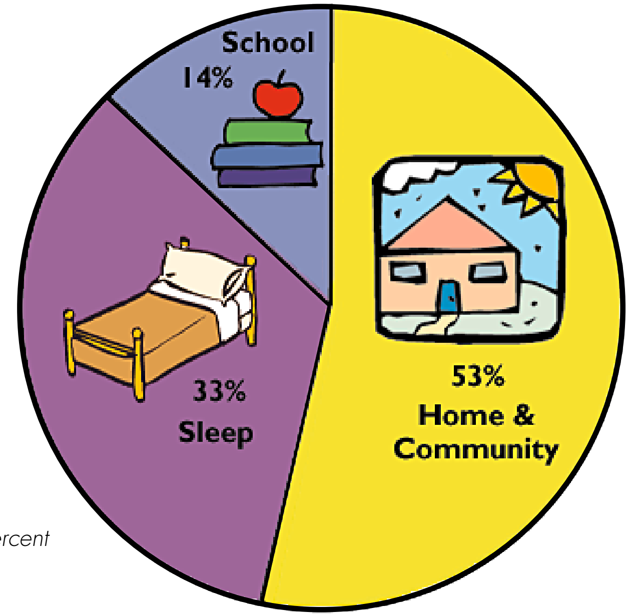


FIGURE 1.2 *Students spend only 14 percent of their time in school.*

Not least, schools need to develop ways to link classroom learning to other aspects of students' lives. Engendering parent support for the core learning principles and parent involvement in the learning process is of utmost importance (Moll, 1990; 1986a, 1986b). Figure 1.2 shows the percentage of time, during a calendar year, that students in a large school district spent in school. If one-third of their time outside school (not counting sleeping) is spent watching television, then students apparently spend more hours per year watching television than attending school. A focus only on the hours that students currently spend in school overlooks the many opportunities for guided learning in other settings.

Applying the Design Framework to Adult Learning

The design framework summarized above assumes that the learners are children, but the principles apply to adult learning as well. This point is particularly important because incorporating the principles in this volume into educational practice will require a good deal of adult learning. Many approaches to teaching adults consistently violate principles for optimizing learning. Professional development programs for teachers, for example, frequently:

- *Are not learner centered.* Rather than ask teachers where they need help, they are simply expected to attend prearranged workshops.
- *Are not knowledge centered.* Teachers may simply be introduced to a new technique (like cooperative learning) without being given the opportunity to understand why, when, where, and how it might be valuable to them. Especially important is the need to integrate the structure of activities with the content of the curriculum that is taught.
- *Are not assessment centered.* In order for teachers to change their practices, they need opportunities to try things out in their classrooms and then receive feedback. Most professional development opportunities do not provide such feedback. Moreover, they tend to focus on change in teaching practice as the goal, but they neglect to develop in teachers the capacity to judge successful transfer of the technique to the classroom or its effects on student achievement.
- *Are not community centered.* Many professional development opportunities are conducted in isolation. Opportunities for continued contact and support as teachers incorporate new ideas into their teaching are limited, yet the rapid spread of Internet access provides a ready means of maintaining such contact if appropriately designed tools and services are available.

The principles of learning and their implications for designing learning environments apply equally to child and adult learning. They provide a lens through which current practice can be viewed with respect to K-12 teaching *and* with respect to preparation of teachers in the research and development agenda. The principles are relevant as well when we consider other groups, such as policy makers and the public, whose learning is also required for educational practice to change.

II

LEARNERS AND LEARNING

2

How Experts Differ from Novices

People who have developed expertise in particular areas are, by definition, able to think effectively about problems in those areas. Understanding expertise is important because it provides insights into the nature of thinking and problem solving. Research shows that it is not simply general abilities, such as memory or intelligence, nor the use of general strategies that differentiate experts from novices. Instead, experts have acquired extensive knowledge that affects what they notice and how they organize, represent, and interpret information in their environment. This, in turn, affects their abilities to remember, reason, and solve problems.

This chapter illustrates key scientific findings that have come from the study of people who have developed expertise in areas such as chess, physics, mathematics, electronics, and history. We discuss these examples *not* because all school children are expected to become experts in these or any other areas, but because the study of expertise shows what the results of successful learning look like. In later chapters we explore what is known about processes of learning that can eventually lead to the development of expertise.

We consider several key principles of experts' knowledge and their potential implications for learning and instruction:

1. Experts notice features and meaningful patterns of information that are not noticed by novices.
2. Experts have acquired a great deal of content knowledge that is organized in ways that reflect a deep understanding of their subject matter.
3. Experts' knowledge cannot be reduced to sets of isolated facts or propositions but, instead, reflects contexts of applicability: that is, the knowledge is "conditionalized" on a set of circumstances.
4. Experts are able to flexibly retrieve important aspects of their knowledge with little attentional effort.
5. Though experts know their disciplines thoroughly, this does not guarantee that they are able to teach others.
6. Experts have varying levels of flexibility in their approach to new situations.

MEANINGFUL PATTERNS OF INFORMATION

One of the earliest studies of expertise demonstrated that the same stimulus is perceived and understood differently, depending on the knowledge that a person brings to the situation. DeGroot (1965) was interested in understanding how world-class chess masters are consistently able to out-think their opponents. Chess masters and less experienced but still extremely good players were shown examples of chess games and asked to think aloud as they decided on the move they would make if they were one of the players; see Box 2.1. DeGroot's hypothesis was that the chess masters would be more likely than the nonmasters to (a) think through all the possibilities before making a move (greater breadth of search) and (b) think through all the possible countermoves of the opponent for every move considered (greater depth of search). In this pioneering research, the chess masters did exhibit considerable breadth and depth to their searches, but so did the lesser ranked chess players. And none of them conducted searches that covered all the possibilities. Somehow, the chess masters considered possibilities for moves that were of higher quality than those considered by the lesser experienced players. Something other than differences in general strategies seemed to be responsible for differences in expertise.

DeGroot concluded that the knowledge acquired over tens of thousands of hours of chess playing enabled chess masters to out-play their opponents. Specifically, masters were more likely to recognize meaningful chess configurations and realize the strategic implications of these situations; this recognition allowed them to consider sets of possible moves that were superior to others. The meaningful patterns seemed readily apparent to the masters, leading deGroot (1965:33-34) to note:

> We know that increasing experience and knowledge in a specific field (chess, for instance) has the effect that things (properties, etc.) which, at earlier stages, had to be abstracted, or even inferred are apt to be immediately perceived at later stages. To a rather large extent, abstraction is replaced by perception, but we do not know much about how this works, nor where the borderline lies. As an effect of this replacement, a so-called 'given' problem situation is not really given since it is seen differently by an expert than it is perceived by an inexperienced person. . . .

DeGroot's think-aloud method provided for a very careful analysis of the conditions of specialized learning and the kinds of conclusions one can draw from them (see Ericsson and Simon, 1993). Hypotheses generated from think-aloud protocols are usually cross-validated through the use of other methodologies.

The superior recall ability of experts, illustrated in the example in the box, has been explained in terms of how they "chunk" various elements of a configuration that are related by an underlying function or strategy. Since there are limits on the amount of information that people can hold in short-term memory, short-term memory is enhanced when people are able to chunk information into familiar patterns (Miller, 1956). Chess masters perceive chunks of meaningful information, which affects their memory for what they see. Chess masters are able to chunk together several chess pieces in a configuration that is governed by some strategic component of the game. Lacking a hierarchical, highly organized structure for the domain, novices cannot use this chunking strategy. It is noteworthy that people do not have to be world-class experts to benefit from their abilities to encode meaningful chunks of information: 10- and 11-year-olds who are experienced in chess are able to remember more chess pieces than college students who are not chess players. In contrast, when the college students were presented with other stimuli, such as strings of numbers, they were able to remember more (Chi, 1978; Schneider et al., 1993); see Figure 2.3.

Skills similar to those of master chess players have been demonstrated for experts in other domains, including electronic circuitry (Egan and Schwartz, 1979), radiology (Lesgold, 1988), and computer programming (Ehrlich and Soloway, 1984). In each case, expertise in a domain helps people develop a sensitivity to patterns of meaningful information that are not available to novices. For example, electronics technicians were able to reproduce large portions of complex circuit diagrams after only a few seconds of viewing; novices could not. The expert circuit technicians chunked several individual circuit elements (e.g., resistors and capacitors) that performed the function of an amplifier. By remembering the structure and function of a typical amplifier, experts were able to recall the arrangement of many of the individual circuit elements comprising the "amplifier chunk."

Mathematics experts are also able to quickly recognize patterns of information, such as particular problem types that involve specific classes of mathematical solutions (Hinsley et al., 1977; Robinson and Hayes, 1978). For example, physicists recognize problems of river currents and problems of headwinds and tailwinds in airplanes as involving similar mathematical principles, such as relative velocities. The expert knowledge that underlies the ability to recognize problem types has been characterized as involving the development of organized conceptual structures, or schemas, that guide how problems are represented and understood (e.g., Glaser and Chi, 1988).

Expert teachers, too, have been shown to have schemas similar to those found in chess and mathematics. Expert and novice teachers were shown a videotaped classroom lesson (Sabers et al., 1991). The experimental set-up involved three screens that showed simultaneous events occurring throughout the classroom (the left, center, and right). During part of the session, the expert and novice teachers were asked to talk aloud about what they were seeing. Later, they were asked questions about classroom events. Overall,

BOX 2.1 **What Experts See**

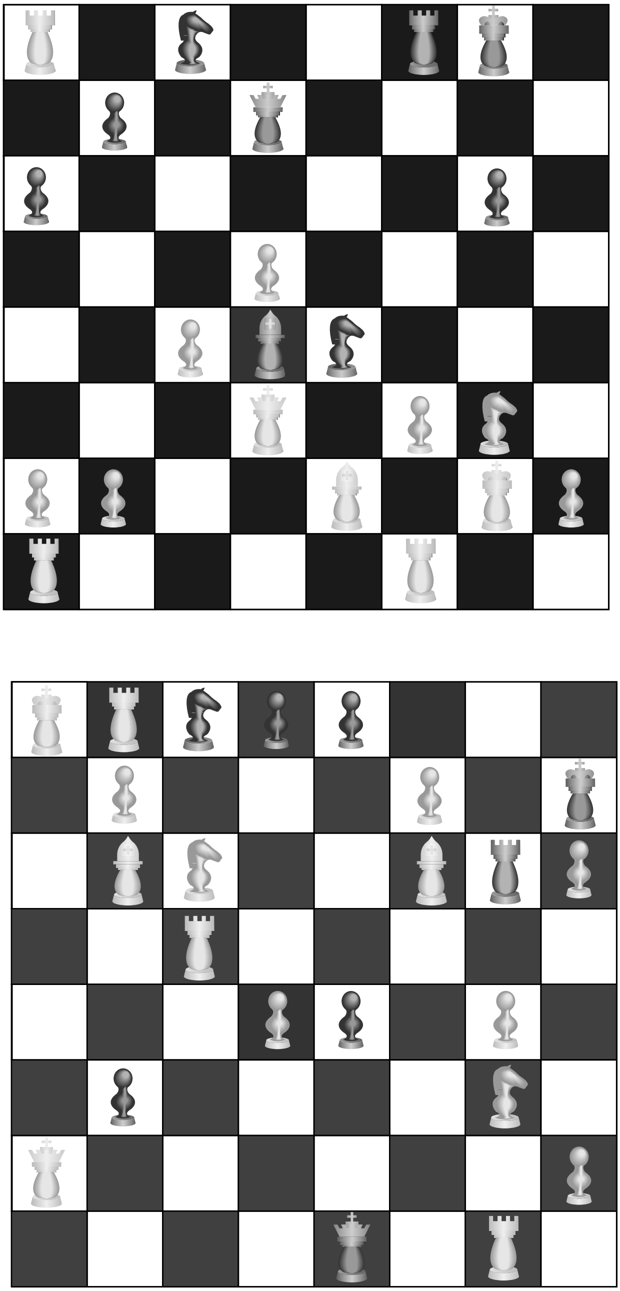


FIGURE 2.1 *Chess board positions used in memory experiments. SOURCE: Adapted from Chase and Simon (1973).*

In one study, a chess master, a Class A player (good but not a master), and a novice were given 5 seconds to view a chess board position from the middle of a chess game; see Figure 2.1. After 5 seconds the board was covered, and each participant attempted to reconstruct the board position on another board. This procedure was repeated for multiple trials until everyone received a perfect score. On the first trial, the master player correctly placed many more pieces than the Class A player, who in turn placed more than the novice: 16, 8, and 4, respectively.

However, these results occurred only when the chess pieces were arranged in configurations that conformed to meaningful games of chess. When chess pieces were randomized and presented for 5 seconds, the recall of the chess master and Class A player were the same as the novice—they placed from 2 to 3 positions correctly. Data over trials for valid and random middle games are shown in Figure 2.2.

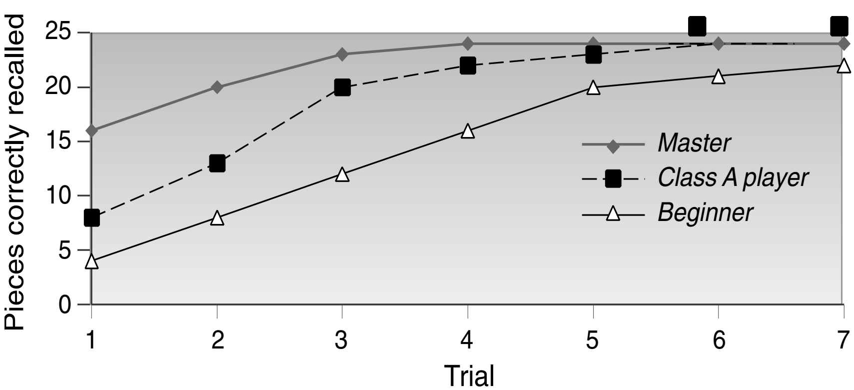


FIGURE 2.2 *Recall by chess players by level of expertise.*

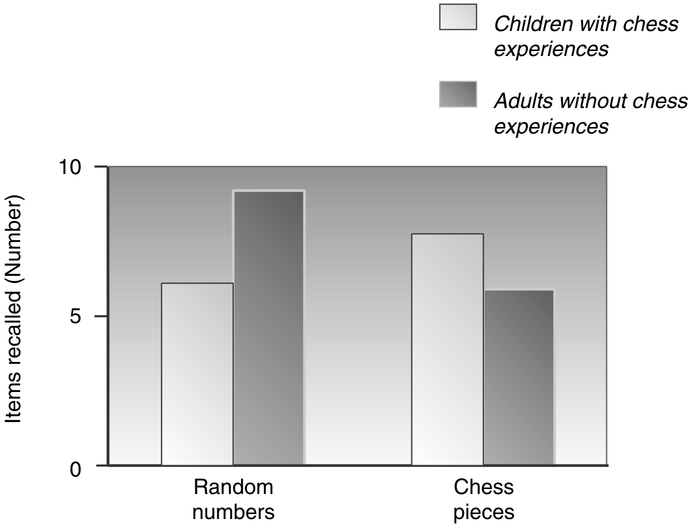


FIGURE 2.3 *Recall for numbers and chess pieces. SOURCE: Adapted from Chi (1978).*

the expert teachers had very different understandings of the events they were watching than did the novice teachers; see examples in Box 2.2.

The idea that experts recognize features and patterns that are not noticed by novices is potentially important for improving instruction. When viewing instructional texts, slides, and videotapes, for example, the information noticed by novices can be quite different from what is noticed by experts (e.g., Sabers et al., 1991; Bransford et al., 1988). One dimension of acquiring greater competence appears to be the increased ability to segment the perceptual field (learning how to see). Research on expertise suggests the importance of providing students with learning experiences that specifically enhance their abilities to recognize meaningful patterns of information (e.g., Simon, 1980; Bransford et al., 1989).

ORGANIZATION OF KNOWLEDGE

We turn now to the question of how experts' knowledge is organized and how this affects their abilities to understand and represent problems. Their knowledge is not simply a list of facts and formulas that are relevant to their domain; instead, their knowledge is organized around core concepts or "big ideas" that guide their thinking about their domains.

BOX 2.2 What Expert and Novice Teachers Notice

Expert and novice teachers notice very different things when viewing a videotape of a classroom lesson.

Expert 6: On the left monitor, the students' note taking indicates that they have seen sheets like this and have had presentations like this before; it's fairly efficient at this point because they're used to the format they are using.

Expert 7: I don't understand why the students can't be finding out this information on their own rather than listening to someone tell them because if you watch the faces of most of them, they start out for about the first 2 or 3 minutes sort of paying attention to what's going on and then just drift off.

Expert 2: . . . I haven't heard a bell, but the students are already at their desks and seem to be doing purposeful activity, and this is about the time that I decide they must be an accelerated group because they came into the room and started something rather than just sitting down and socializing.

Novice 1: . . . I can't tell what they are doing. They're getting ready for class, but I can't tell what they're doing.

Novice 3: She's trying to communicate with them here about something, but I sure couldn't tell what it was.

Another novice: It's a lot to watch.

In an example from physics, experts and competent beginners (college students) were asked to describe verbally the approach they would use to solve physics problems. Experts usually mentioned the major principle(s) or law(s) that were applicable to the problem, together with a rationale for why those laws applied to the problem and how one could apply them (Chi et al., 1981). In contrast, competent beginners rarely referred to major principles and laws in physics; instead, they typically described which equations they would use and how those equations would be manipulated (Larkin, 1981, 1983).

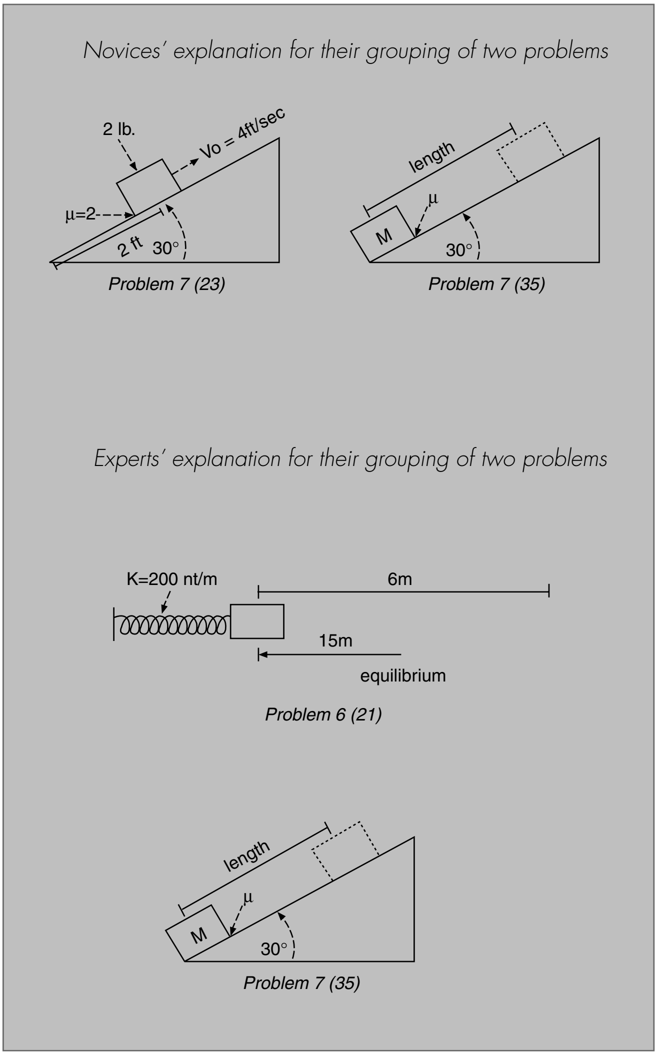
Experts' thinking seems to be organized around big ideas in physics, such as Newton's second law and how it would apply, while novices tend to perceive problem solving in physics as memorizing, recalling, and manipulating equations to get answers. When solving problems, experts in physics often pause to draw a simple qualitative diagram—they do not simply attempt to plug numbers into a formula. The diagram is often elaborated as the expert seeks to find a workable solution path (e.g., see Larkin et al., 1980; Larkin and Simon, 1987; Simon and Simon, 1978).

Differences in how physics experts and novices approach problems can also be seen when they are asked to sort problems, written on index cards, according to the approach that could be used to solve them (Chi et al., 1981). Experts' problem piles are arranged on the basis of the principles that can be applied to solve the problems; novices' piles are arranged on the basis of the problems' surface attributes. For example, in the physics subfield of mechanics, an expert's pile might consist of problems that can be solved by conservation of energy, while a novice's pile might consist of problems that contain inclined planes; see Figure 2.4. Responding to the surface characteristics of problems is not very useful, since two problems that share the same objects and look very similar may actually be solved by entirely different approaches.

Some studies of experts and novices in physics have explored the organization of the knowledge structures that are available to these different groups of individuals (Chi et al., 1982); see Figure 2.5. In representing a schema for an incline plane, the novice's schema contains primarily surface features of the incline plane. In contrast, the expert's schema immediately connects the notion of an incline plane with the laws of physics and the conditions under which laws are applicable.

Pause times have also been used to infer the structure of expert knowledge in domains such as chess and physics. Physics experts appear to evoke sets of related equations, with the recall of one equation activating related equations that are retrieved rapidly (Larkin, 1979). Novices, in contrast, retrieve equations more equally spaced in time, suggesting a sequential search in memory. Experts appear to possess an efficient organization of knowledge with meaningful relations among related elements clustered into related units that are governed by underlying concepts and principles; see Box 2.3. Within this picture of expertise, "knowing more" means having more conceptual chunks in memory, more relations or features defining each chunk, more interrelations among the chunks, and efficient methods for retrieving related chunks and procedures for applying these informational units in problem-solving contexts (Chi et al., 1981).

Differences between how experts and nonexperts organize knowledge has also been demonstrated in such fields as history (Wineburg, 1991). A group of history experts and a group of gifted, high-achieving high school seniors enrolled in an advanced placement course in history were first given a test of facts about the American Revolution. The historians with back-



Explanations

Novice 1: These deal with blocks on an incline plane.

Novice 5: Incline plane problems, coefficient of friction.

Novice 6: Blocks on inclined planes with angles.

Explanations

Expert 2: Conservation of energy.

Expert 3: Work-theory theorem. They are all straight-forward problems.

Expert 4: These can be done from energy considerations. Either you should know the principle of conservation of energy, or work is lost somewhere.

FIGURE 2.4 *An example of sortings of physics problems made by novices and experts. Each picture above represents a diagram that can be drawn from the storyline of a physics problem taken from an introductory physics textbook. The novices and experts in this study were asked to categorize many such problems based on similarity of solution. The two pairs show a marked contrast in the experts' and novices' categorization schemes. Novices tend to categorize physics problems as being solved similarly if they "look the same" (that is, share the same surface features), whereas experts categorize according to the major principle that could be applied to solve the problems.*
SOURCE: Adapted from Chi et al. (1981).

Permission to post Figure 2.5 on the Web denied.
Figure is printed in the book but is not available online.

BOX 2.3 Understanding and Problem Solving

In mathematics, experts are more likely than novices to first try to understand problems, rather than simply attempt to plug numbers into formulas. Experts and students in one study (Paige and Simon, 1966) were asked to solve algebra word problems, such as:

> A board was sawed into two pieces. One piece was two-thirds as long as the whole board and was exceeded in length by the second piece by four feet. How long was the board before it was cut?

The experts quickly realize that the problem as stated is logically impossible. Although some students also come to this realization, others simply apply equations, which results in the answer of a negative length.

A similar example comes from a study of adults and children (Reusser, 1993), who were asked:

> There are 26 sheep and 10 goats on a ship. How old is the captain?

Most adults have enough expertise to realize that this problem is unsolvable, but many school children didn't realize this at all. More than three-quarters of the children in one study attempted to provide a numerical answer to the problems. They asked themselves whether to add, subtract, multiply, or divide, rather than whether the problem made sense. As one fifth-grade child explained, after giving the answer of 36: "Well, you need to add or subtract or multiply in problems like this, and this one seemed to work best if I add" (Bransford and Stein, 1993:196).

grounds in American history knew most of the items. However, many of the historians had specialties that lay elsewhere and they knew only one-third of the facts on the tests. Several of the students outscored several of the historians on the factual test. The study then compared how the historians and students made sense of historical documents; the result revealed dramatic differences on virtually any criterion. The historians excelled in the elaborateness of understandings they developed in their ability to pose alternative explanations for events and in their use of corroborating evidence. This depth of understanding was as true for the Asian specialists and the medievalists as it was for the Americanists.

When the two groups were asked to select one of three pictures that best reflect their understanding of the battle of Lexington, historians and students displayed the greatest differences. Historians carefully navigated back and forth between the corpus of written documents and the three images of the battlefield. For them, the picture selection task was the quintessential epistemological exercise, a task that explored the limits of historical knowledge. They knew that no single document or picture could tell the story of history; hence, they thought very hard about their choices. In contrast, the students generally just looked at the pictures and made a selection without regard or qualification. For students, the process was similar to finding the correct answer on a multiple choice test.

In sum, although the students scored very well on facts about history, they were largely unacquainted with modes of inquiry with real historical thinking. They had no systematic way of making sense of contradictory claims. Thrust into a set of historical documents that demanded that they sort out competing claims and formulate a reasoned interpretation, the students, on the whole, were stymied. They lacked the experts' deep understanding of how to formulate reasoned interpretations of sets of historical documents. Experts in other social sciences also organize their problem solving around big ideas (see, e.g., Voss et al., 1984).

The fact that experts' knowledge is organized around important ideas or concepts suggests that curricula should also be organized in ways that lead to conceptual understanding. Many approaches to curriculum design make it difficult for students to organize knowledge meaningfully. Often there is only superficial coverage of facts before moving on to the next topic; there is little time to develop important, organizing ideas. History texts sometimes emphasize facts without providing support for understanding (e.g., Beck et al., 1989, 1991). Many ways of teaching science also overemphasize facts (American Association for the Advancement of Science, 1989; National Research Council, 1996).

The Third International Mathematics and Science Survey (TIMSS) (Schmidt et al., 1997) criticized curricula that were "a mile wide and an inch deep" and argued that this is much more of a problem in America than in most other countries. Research on expertise suggests that a superficial coverage of many topics in the domain may be a poor way to help students develop the competencies that will prepare them for future learning and work. The idea of helping students organize their knowledge also suggests that novices might benefit from models of how experts approach problem solving—especially if they then receive coaching in using similar strategies (e.g., Brown et al., 1989; we discuss this more fully in Chapters 3 and 7).

CONTEXT AND ACCESS TO KNOWLEDGE

Experts have a vast repertoire of knowledge that is relevant to their domain or discipline, but only a subset of that knowledge is relevant to any particular problem. Experts do not have to search through everything they know in order to find what is relevant; such an approach would overwhelm their working memory (Miller, 1956). For example, the chess masters described above considered only a subset of possible chess moves, but those moves were generally superior to the ones considered by the lesser ranked players. Experts have not only acquired knowledge, but are also good at retrieving the knowledge that is relevant to a particular task. In the language of cognitive scientists, experts' knowledge is "conditionalized"—it includes a specification of the contexts in which it is useful (Simon, 1980; Glaser, 1992). Knowledge that is not conditionalized is often "inert" because it is not activated, even though it is relevant (Whitehead, 1929).

The concept of conditionalized knowledge has implications for the design of curriculum, instruction, and assessment practices that promote effective learning. Many forms of curricula and instruction do not help students conditionalize their knowledge: "Textbooks are much more explicit in enunciating the laws of mathematics or of nature than in saying anything about when these laws may be useful in solving problems" (Simon, 1980:92). It is left largely to students to generate the condition-action pairs required for solving novel problems.

One way to help students learn about conditions of applicability is to assign word problems that require students to use appropriate concepts and formulas (Lesgold, 1984, 1988; Simon, 1980). If well designed, these problems can help students learn when, where, and why to use the knowledge they are learning. Sometimes, however, students can solve sets of practice problems but fail to conditionalize their knowledge because they know which chapter the problems came from and so automatically use this information to decide which concepts and formulas are relevant. Practice problems that are organized into very structured worksheets can also cause this problem. Sometimes students who have done well on such assignments—and believe that they are learning—are unpleasantly surprised when they take tests in which problems from the entire course are randomly presented so there are no clues about where they appeared in a text (Bransford, 1979).

The concept of conditionalized knowledge also has important implications for assessment practices that provide feedback about learning. Many types of tests fail to help teachers and students assess the degree to which the students' knowledge is conditionalized. For example, students might be asked whether the formula that quantifies the relationship between mass and energy is $E = MC$, $E = MC^2$, or $E = MC^3$. A correct answer requires no knowledge of the conditions under which it is appropriate to use the formula. Similarly, students in a literature class might be asked to explain the meaning of familiar proverbs, such as "he who hesitates is lost" or "too many cooks spoil the broth." The ability to explain the meaning of each proverb provides no guarantee that students will know the conditions under which either proverb is useful. Such knowledge is important because, when viewed solely as propositions, proverbs often contradict one another. To use them effectively, people need to know when and why it is appropriate to apply the maxim "too many cooks spoil the broth" versus "many hands make light work" or "he who hesitates is lost" versus "haste makes waste" (see Bransford and Stein, 1993).

FLUENT RETRIEVAL

People's abilities to retrieve relevant knowledge can vary from being "effortful" to "relatively effortless" (fluent) to "automatic" (Schneider and Shiffrin, 1977). Automatic and fluent retrieval are important characteristics of expertise.

Fluent retrieval does not mean that experts always perform a task faster than novices. Because experts attempt to understand problems rather than to jump immediately to solution strategies, they sometimes take more time than novices (e.g., Getzels and Csikszentmihalyi, 1976). But within the overall process of problem solving there are a number of subprocesses that, for experts, vary from fluent to automatic. Fluency is important because effortless processing places fewer demands on conscious attention. Since the amount of information a person can attend to at any one time is limited (Miller, 1956), ease of processing some aspects of a task gives a person more capacity to attend to other aspects of the task (LaBerge and Samuels, 1974; Schneider and Shiffrin, 1985; Anderson, 1981, 1982; Lesgold et al., 1988).

Learning to drive a car provides a good example of fluency and automaticity. When first learning, novices cannot drive and simultaneously carry on a conversation. With experience, it becomes easy to do so. Similarly, novice readers whose ability to decode words is not yet fluent are unable to devote attention to the task of understanding what they are reading (LaBerge and Samuels, 1974). Issues of fluency are very important for understanding learning and instruction. Many instructional environments stop short of helping all students develop the fluency needed to successfully perform cognitive tasks (Beck et al., 1989; Case, 1978; Hasselbring et al., 1987; LaBerge and Samuels, 1974).

An important aspect of learning is to become fluent at recognizing problem types in particular domains—such as problems involving Newton's second law or concepts of rate and functions—so that appropriate solutions can be easily retrieved from memory. The use of instructional procedures that speed pattern recognition are promising in this regard (e.g., Simon, 1980).

EXPERTS AND TEACHING

Expertise in a particular domain does not guarantee that one is good at helping others learn it. In fact, expertise can sometimes hurt teaching because many experts forget what is easy and what is difficult for students.

Recognizing this fact, some groups who design educational materials pair content area experts with "accomplished novices" whose area of expertise lies elsewhere: their task is to continually challenge the experts until the experts' ideas for instruction begin to make sense to them (Cognition and Technology Group at Vanderbilt, 1997).

The content knowledge necessary for expertise in a discipline needs to be differentiated from the pedagogical content knowledge that underlies effective teaching (Redish, 1996; Shulman, 1986, 1987). The latter includes information about typical difficulties that students encounter as they attempt to learn about a set of topics; typical paths students must traverse in order to achieve understanding; and sets of potential strategies for helping students overcome the difficulties that they encounter. Shulman (1986, 1987) argues that pedagogical content knowledge is not equivalent to knowledge of a content domain plus a generic set of teaching strategies; instead, teaching strategies differ across disciplines. Expert teachers know the kinds of difficulties that students are likely to face; they know how to tap into students' existing knowledge in order to make new information meaningful; and they know how to assess their students' progress. Expert teachers have acquired pedagogical content knowledge as well as content knowledge; see Box 2.4. In the absence of pedagogical content knowledge, teachers often rely on textbook publishers for decisions about how to best organize subjects for students. They are therefore forced to rely on the "prescriptions of absentee curriculum developers" (Brophy, 1983), who know nothing about the particular students in each teacher's classroom. Pedagogical content knowledge is an extremely important part of what teachers need to learn to be more effective. (This topic is discussed more fully in Chapter 7.)

ADAPTIVE EXPERTISE

An important question for educators is whether some ways of organizing knowledge are better at helping people remain flexible and adaptive to new situations than others. For example, contrast two types of Japanese sushi experts (Hatano and Inagaki, 1986): one excels at following a fixed recipe; the other has "adaptive expertise" and is able to prepare sushi quite creatively. These appear to be examples of two very different types of expertise, one that is relatively routinized and one that is flexible and more adaptable to external demands: experts have been characterized as being "merely skilled" versus "highly competent" or more colorfully as "artisans" versus "virtuosos" (Miller, 1978). These differences apparently exist across a wide range of jobs.

One analysis looked at these differences in terms of information systems design (Miller, 1978). Information systems designers typically work with clients who specify what they want. The goal of the designer is to construct systems that allow people to efficiently store and access relevant informa-

BOX 2.4 Teaching *Hamlet*

Two new English teachers, Jake and Steven, with similar subject-matter backgrounds from elite private universities, set out to teach *Hamlet* in high school (Grossman, 1990).

In his teaching, Jake spent 7 weeks leading his students through a word-by-word *explication du texte*, focusing on notions of "linguistic reflexivity," and issues of modernism. His assignments included in-depth analyses of soliloquies, memorization of long passages, and a final paper on the importance of language in *Hamlet*. Jake's model for this instruction was his own undergraduate coursework; there was little transformation of his knowledge, except to parcel it out in chunks that fit into the 50-minute containers of the school day. Jake's image for how students would respond was his own responses as a student who loved Shakespeare and delighted in close textual analysis. Consequently, when students responded in less than enthusiastic ways, Jake was ill-equipped to understand their confusion: "The biggest problem I have with teaching by far is trying to get into the mind-set of a ninth grader . . . "

Steven began his unit on *Hamlet* without ever mentioning the name of the play. To help his students grasp the initial outline of the themes and issues of the play, he asked them to imagine that their parents had recently divorced and that their mothers had taken up with a new man. This new man had replaced their father at work, and "there's some talk that he had something to do with the ousting of your dad" (Grossman, 1990:24). Steven then asked students to think about the circumstances that might drive them so mad that they would contemplate murdering another human being. Only then, after students had contemplated these issues and done some writing on them, did Steven introduce the play they would be reading.

tion (usually through computers). Artisan experts seek to identify the functions that their clients want automated; they tend to accept the problem and its limits as stated by the clients. They approach new problems as opportunities to use their existing expertise to do familiar tasks more efficiently. It is important to emphasize that artisans' skills are often extensive and should not be underestimated. In contrast, however, the virtuoso experts treat the client's statement of the problem with respect, but consider it "a point for departure and exploration" (Miller, 1978). They view assignments as opportunities to explore and expand their current levels of expertise. Miller also observes that, in his experience, virtuosos exhibit their positive characteristics *despite* their training, which is usually restricted solely to technical skills.

The concept of adaptive expertise has also been explored in a study of history experts (Wineburg, 1998). Two history experts and a group of future teachers were asked to read and interpret a set of documents about Abraham Lincoln and his view of slavery. This is a complex issue that, for Lincoln, involved conflicts between enacted law (the Constitution), natural law (as encoded in the Declaration of Independence), and divine law (assumptions about basic rights). One of the historians was an expert on Lincoln; the second historian's expertise lay elsewhere. The Lincoln expert brought detailed content knowledge to the documents and easily interpreted them; the other historian was familiar with some of the broad themes in the documents but quickly became confused in the details. In fact, at the beginning of the task, the second historian reacted no differently than a group of future high school teachers who were faced with the same task (Wineburg and Fournier, 1994): attempting to harmonize discrepant information about Lincoln's position, they both appealed to an array of present social forms and institutions—such as speech writers, press conferences, and "spin doctors"—to explain why things seemed discrepant. Unlike the future teachers, however, the second historian did not stop with his initial analysis. He instead adopted a working hypothesis that assumed that the apparent contradictions might be rooted less in Lincoln's duplicity than in his own ignorance of the nineteenth century. The expert stepped back from his own initial interpretation and searched for a deeper understanding of the issues. As he read texts from this perspective, his understanding deepened, and he learned from the experience. After considerable work, the second historian was able to piece together an interpretive structure that brought him by the task's end to where his more knowledgeable colleague had begun. The future history teachers, in contrast, never moved beyond their initial interpretations of events.

An important characteristic exhibited by the history expert involves what is known as "metacognition"—the ability to monitor one's current level of understanding and decide when it is not adequate. The concept of metacognition was originally introduced in the context of studying young children (e.g., Brown, 1980; Flavell, 1985, 1991). For example, young children often erroneously believe that they can remember information and hence fail to use effective strategies, such as rehearsal. The ability to recognize the limits of one's current knowledge, then take steps to remedy the situation, is extremely important for learners at all ages. The history expert who was not a specialist in Lincoln was metacognitive in the sense that he successfully recognized the insufficiency of his initial attempts to explain Lincoln's position. As a consequence, he adopted the working hypothesis that he needed to learn more about the context of Lincoln's times before coming to a reasoned conclusion.

Beliefs about what it means to be an expert can affect the degree to which people explicitly search for what they don't know and take steps to improve the situation. In a study of researchers and veteran teachers, a common assumption was that "an expert is someone who knows all the answers" (Cognition and Technology Group at Vanderbilt, 1997). This assumption had been implicit rather than explicit and had never been questioned and discussed. But when the researchers and teachers discussed this concept, they discovered that it placed severe constraints on new learning because the tendency was to worry about looking competent rather than publicly acknowledging the need for help in certain areas (see Dweck, 1989, for similar findings with students). The researchers and the teachers found it useful to replace their previous model of "answer-filled experts" with the model of "accomplished novices." Accomplished novices are skilled in many areas and proud of their accomplishments, but they realize that what they know is minuscule compared to all that is potentially knowable. This model helps free people to continue to learn even though they may have spent 10 to 20 years as an "expert" in their field.

The concept of adaptive expertise (Hatano and Inagaki, 1986) provides an important model of successful learning. Adaptive experts are able to approach new situations flexibly and to learn throughout their lifetimes. They not only use what they have learned, they are metacognitive and continually question their current levels of expertise and attempt to move beyond them. They don't simply attempt to do the same things more efficiently; they attempt to do things better. A major challenge for theories of learning is to understand how particular kinds of learning experiences develop adaptive expertise or "virtuosos."

CONCLUSION

Experts' abilities to reason and solve problems depend on well-organized knowledge that affects what they notice and how they represent problems. Experts are not simply "general problem solvers" who have learned a set of strategies that operate across all domains. The fact that experts are more likely than novices to recognize meaningful patterns of information applies in all domains, whether chess, electronics, mathematics, or classroom teaching. In deGroot's (1965) words, a "given" problem situation is not really a given. Because of their ability to see patterns of meaningful information, experts begin problem solving at "a higher place" (deGroot, 1965). An emphasis on the patterns perceived by experts suggests that pattern recognition is an important strategy for helping students develop confidence and competence. These patterns provide triggering conditions for accessing knowledge that is relevant to a task.

Studies in areas such as physics, mathematics, and history also demonstrate that experts first seek to develop an understanding of problems, and this often involves thinking in terms of core concepts or big ideas, such as Newton's second law in physics. Novices' knowledge is much less likely to be organized around big ideas; they are more likely to approach problems by searching for correct formulas and pat answers that fit their everyday intuitions.

Curricula that emphasize breadth of knowledge may prevent effective organization of knowledge because there is not enough time to learn anything in depth. Instruction that enables students to see models of how experts organize and solve problems may be helpful. However, as discussed in more detail in later chapters, the level of complexity of the models must be tailored to the learners' current levels of knowledge and skills.

While experts possess a vast repertoire of knowledge, only a subset of it is relevant to any particular problem. Experts do not conduct an exhaustive search of everything they know; this would overwhelm their working memory (Miller, 1956). Instead, information that is relevant to a task tends to be selectively retrieved (e.g., Ericsson and Staszewski, 1989; deGroot, 1965).

The issue of retrieving relevant information provides clues about the nature of usable knowledge. Knowledge must be "conditionalized" in order to be retrieved when it is needed; otherwise, it remains inert (Whitehead, 1929). Many designs for curriculum instruction and assessment practices fail to emphasize the importance of conditionalized knowledge. For example, texts often present facts and formulas with little attention to helping students learn the conditions under which they are most useful. Many assessments measure only propositional (factual) knowledge and never ask whether students know when, where, and why to use that knowledge.

Another important characteristic of expertise is the ability to retrieve relevant knowledge in a manner that is relatively "effortless." This fluent retrieval does not mean that experts always accomplish tasks in less time than novices; often they take more time in order to fully understand a problem. But their ability to retrieve information effortlessly is extremely important because fluency places fewer demands on conscious attention, which is limited in capacity (Schneider and Shiffrin, 1977, 1985). Effortful retrieval, by contrast, places many demands on a learner's attention: attentional effort is being expended on remembering instead of learning. Instruction that focuses solely on accuracy does not necessarily help students develop fluency (e.g., Beck et al., 1989; Hasselbring et al., 1987; LaBerge and Samuels, 1974).

Expertise in an area does not guarantee that one can effectively teach others about that area. Expert teachers know the kinds of difficulties that students are likely to face, and they know how to tap into their students' existing knowledge in order to make new information meaningful plus assess their students' progress. In Shulman's (1986, 1987) terms, expert teachers have acquired pedagogical content knowledge and not just content knowledge. (This concept is explored more fully in Chapter 7.)

The concept of adaptive expertise raises the question of whether some ways of organizing knowledge lead to greater flexibility in problem solving than others (Hatano and Inagaki, 1986; Spiro et al., 1991). Differences between the "merely skilled" (artisans) and the "highly competent" (virtuosos) can be seen in fields as disparate as sushi making and information design. Virtuosos not only apply expertise to a given problem, they also consider whether the problem as presented is the best way to begin.

The ability to monitor one's approach to problem solving—to be metacognitive—is an important aspect of the expert's competence. Experts step back from their first, oversimplistic interpretation of a problem or situation and question their own knowledge that is relevant. People's mental models of what it means to be an expert can affect the degree to which they learn throughout their lifetimes. A model that assumes that experts know all the answers is very different from a model of the accomplished novice, who is proud of his or her achievements and yet also realizes that there is much more to learn.

We close this chapter with two important cautionary notes. First, the six principles of expertise need to be considered simultaneously, as parts of an overall system. We divided our discussion into six points in order to facilitate explanation, but each point interacts with the others; this interrelationship has important educational implications. For example, the idea of promoting fluent access to knowledge (principle 4) must be approached with an eye toward helping students develop an understanding of the subject matter (principle 2), learn when, where and why to use information (principle 3), and learn to recognize meaningful patterns of information (principle 1). Furthermore, all these need to be approached from the perspective of helping students develop adaptive expertise (principle 6), which includes helping them become metacognitive about their learning so that they can assess their own progress and continually identify and pursue new learning goals. An example in mathematics is getting students to recognize when a proof is needed. Metacognition can help students develop personally relevant pedagogical content knowledge, analogous to the pedagogical content knowledge available to effective teachers (principle 5). In short, students need to develop the ability to teach themselves.

The second cautionary note is that although the study of experts provides important information about learning and instruction, it can be misleading if applied inappropriately. For example, it would be a mistake simply to expose novices to expert models and assume that the novices will learn effectively; what they will learn depends on how much they know already. Discussions in the next chapters (3 and 4) show that effective instruction begins with the knowledge and skills that learners bring to the learning task.

3

Learning and Transfer

Processes of learning and the transfer of learning are central to understanding how people develop important competencies. Learning is important because no one is born with the ability to function competently as an adult in society. It is especially important to understand the kinds of learning experiences that lead to transfer, defined as the ability to extend what has been learned in one context to new contexts (e.g., Byrnes, 1996:74). Educators hope that students will transfer learning from one problem to another within a course, from one year in school to another, between school and home, and from school to workplace. Assumptions about transfer accompany the belief that it is better to broadly "educate" people than simply "train" them to perform particular tasks (e.g., Broudy, 1977).

Measures of transfer play an important role in assessing the quality of people's learning experiences. Different kinds of learning experiences can look equivalent when tests of learning focus solely on remembering (e.g., on the ability to repeat previously taught facts or procedures), but they can look quite different when tests of transfer are used. Some kinds of learning experiences result in effective memory but poor transfer; others produce effective memory plus positive transfer.

Thorndike and his colleagues were among the first to use transfer tests to examine assumptions about learning (e.g., Thorndike and Woodworth, 1901). One of their goals was to test the doctrine of "formal discipline" that was prevalent at the turn of the century. According to this doctrine, practice by learning Latin and other difficult subjects had broad-based effects, such as developing general skills of learning and attention. But these studies raised serious questions about the fruitfulness of designing educational experiences based on the assumption of formal discipline. Rather than developing some kind of "general skill" or "mental muscle" that affected a wide range of performances, people seemed to learn things that were more specific; see Box 3.1.

Early research on the transfer of learning was guided by theories that emphasized the similarity between conditions of learning and conditions of transfer. Thorndike (1913), for example, hypothesized that the degree of transfer between initial and later learning depends upon the match between

BOX 3.1 What People Learn

Ericsson et al. (1980) worked extensively with a college student for well over a year, increasing his capacity to remember digit strings (e.g., 982761093 . . .). As expected, at the outset he could remember only about seven numbers. After practice, he could remember 70 or more; see Figure 3.1. How? Did he develop a general skill analogous to strengthening a "mental muscle?" No, what happened was that he learned to use his specific background knowledge to "chunk" information into meaningful groups. The student had extensive knowledge about winning times for famous track races, including the times of national and world records. For example 941003591992100 could be chunked into 94100 (9.41 seconds for 100 yards). 3591 (3 minutes, 59.1 seconds for a mile), etc. But it took the student a huge amount of practice before he could perform at his final level, and when he was tested with *letter* strings, he was back to remembering about seven items.

SOURCE: Ericsson et al. (1980:1181-1182). Reprinted by permission.

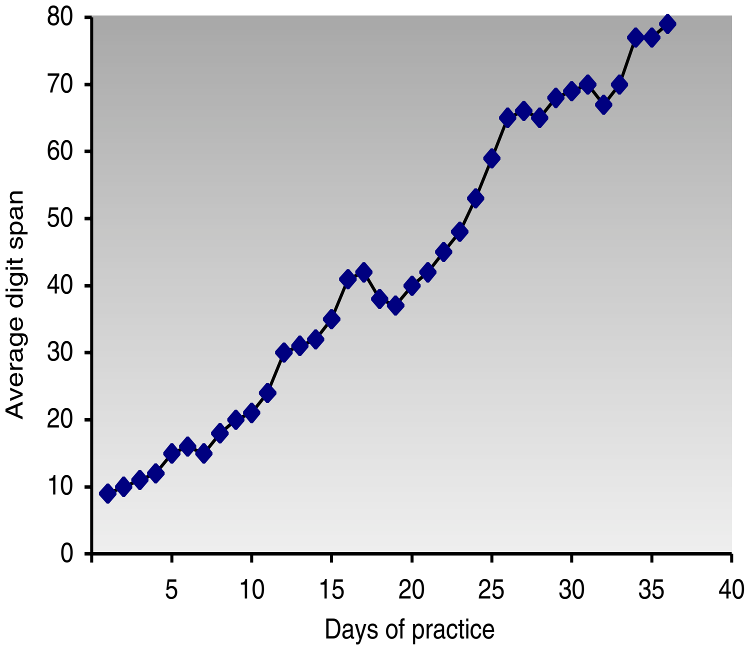


FIGURE 3.1 *Change in average digit span remembered.*

elements across the two events. The essential elements were presumed to be specific facts and skills. By such an account, skills of writing letters of the alphabet are useful to writing words (vertical transfer). The theory posited that transfer from one school task and a highly similar task (near transfer), and from school subjects to nonschool settings (far transfer), could be facilitated by teaching knowledge and skills in school subjects that have elements *identical* to activities encountered in the transfer context (Klausmeier, 1985). Transfer could also be negative in the sense that experience with one set of events could hurt performance on related tasks (Luchins and Luchins, 1970); see Box 3.2.

The emphasis on identical elements of tasks excluded consideration of any learner characteristics, including when attention was directed, whether relevant principles were extrapolated, problem solving, or creativity and motivation. The primary emphasis was on drill and practice. Modern theories of learning and transfer retain the emphasis on practice, but they specify the kinds of practice that are important and take learner characteristics (e.g., existing knowledge and strategies) into account (e.g., Singley and Anderson, 1989).

In the discussion below we explore key characteristics of learning and transfer that have important implications for education:

- Initial learning is necessary for transfer, and a considerable amount is known about the kinds of learning experiences that support transfer.
- Knowledge that is overly contextualized can reduce transfer; abstract representations of knowledge can help promote transfer.
- Transfer is best viewed as an active, dynamic process rather than a passive end-product of a particular set of learning experiences.
- All new learning involves transfer based on previous learning, and this fact has important implications for the design of instruction that helps students learn.

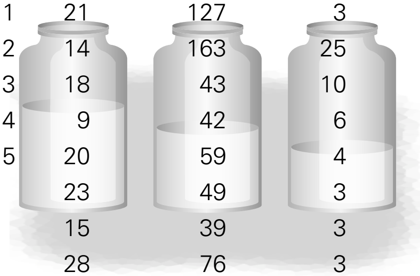
ELEMENTS THAT PROMOTE INITIAL LEARNING

The first factor that influences successful transfer is degree of mastery of the original subject. Without an adequate level of initial learning, transfer cannot be expected. This point seems obvious, but it is often overlooked.

The importance of initial learning is illustrated by a series of studies designed to assess the effects of learning to program in the computer language LOGO. The hypothesis was that students who learned LOGO would transfer this knowledge to other areas that required thinking and problem solving (Papert, 1980). Yet in many cases, the studies found no differences on transfer tests between students who had been taught LOGO and those who had not (see Cognition and Technology Group at Vanderbilt, 1996;

BOX 3.2 An Example of Negative Transfer

Luchins and Luchins (1970) studied how prior experience can limit people's abilities to function efficiently in new settings. They used water jar problems where participants had three jars of varying sizes and an unlimited water supply and were asked to obtain a required amount of water. Everyone received a practice problem. People in the experimental group then received five problems (problems 2-6) prior to critical test problems (7, 8, 10, and 11). People in the control group went straight from the practice problems to problems 7-11. Problems 2-6 were designed to establish a "set" (Einstellung) for solving the problems in a particular manner (using containers b-a-2c as a solution). People in the experimental group were highly likely to use the Einstellung Solution on the critical problems even though more efficient procedures were available. In contrast, people in the control group used solutions that were much more direct.

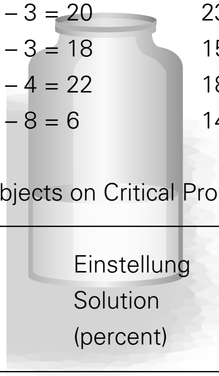


	Given Jars of the Following Sizes			Obtain the
Problem	A	B	C	Amount
1	29	3		20
2 Einstellung 1	21	127	3	100
3 Einstellung 2	14	163	25	99
4 Einstellung 3	18	43	10	5
5 Einstellung 4	9	42	6	21
6 Einstellung 5	20	59	4	31
7 Critical 1	23	49	3	20
8 Critical 2	15	39	3	18
9	28	76	3	25
10 Critical 3	18	48	4	22
11 Critical 4	14	36	8	6

BOX 3.2 An Example of Negative Transfer (*continued*)

Possible Answers for Critical Problems (7, 8, 10, 11)

Problem	Einstellung Solution	Direct Solution
7	49 – 23 – 3 – 3 = 20	23 – 3 = 20
8	39 – 15 – 3 – 3 = 18	15 + 3 = 18
10	48 – 18 – 4 – 4 = 22	18 + 4 = 22
11	36 – 14 – 8 – 8 = 6	14 – 8 = 6



Performance of Typical Subjects on Critical Problems

Group	Einstellung Solution (percent)	Direct Solution (percent)	No Solution (percent)
Control (Children)	1	89	10
Experimental (Children)	72	24	4
Control (Adults)	0	100	0
Experimental (Adults)	74	26	0

SOURCE: Adapted from Luchins and Luchins (1970).

Mayer, 1988). However, many of these studies failed to assess the degree to which LOGO was learned in the first place (see Klahr and Carver, 1988; Littlefield et al., 1988). When initial learning was assessed, it was found that students often had not learned enough about LOGO to provide a basis for transfer. Subsequent studies began to pay more attention to student learning, and they did find transfer to related tasks (Klahr and Carver, 1988; Littlefield et al., 1988). Other research studies have shown that additional qualities of initial learning affect transfer and are reviewed next.

Understanding Versus Memorizing

Transfer is affected by the degree to which people learn with understanding rather than merely memorize sets of facts or follow a fixed set of procedures; see Boxes 3.3 and 3.4.

In Chapter 1, the advantages of learning with understanding were illus-

BOX 3.3 Throwing Darts

In one of the most famous early studies comparing the effects of "learning a procedure" with "learning with understanding," two groups of children practiced throwing darts at a target underwater (Scholckow and Judd, described in Judd, 1908; see a conceptual replication by Hendrickson and Schroeder, 1941). One group received an explanation of refraction of light, which causes the apparent location of the target to be deceptive. The other group only practiced dart throwing, without the explanation. Both groups did equally well on the practice task, which involved a target 12 inches under water. But the group that had been instructed about the abstract principle did much better when they had to transfer to a situation in which the target was under only 4 inches of water. Because they understood what they were doing, the group that had received instruction about the refraction of light could adjust their behavior to the new task.

trated with an example from biology that involved learning about the physical properties of veins and arteries. We noted that the ability to remember properties of veins and arteries (e.g., that arteries are thicker than veins, more elastic, and carry blood from the heart) is not the same as understanding why they have particular properties. The ability to understand becomes important for transfer problems, such as: "Imagine trying to design an artificial artery. Would it have to be elastic? Why or why not?" Students who only memorize facts have little basis for approaching this kind of problem-solving task (Bransford and Stein, 1993; Bransford et al., 1983). The act of organizing facts about veins and arteries around more general principles such as "how structure is related to function" is consistent with the knowledge organization of experts discussed in Chapter 2.

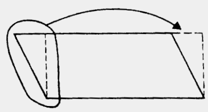
Time to Learn

It is important to be realistic about the amount of time it takes to learn complex subject matter. It has been estimated that world-class chess masters require from 50,000 to 100,000 hours of practice to reach that level of expertise; they rely on a knowledge base containing some 50,000 familiar chess patterns to guide their selection of moves (Chase and Simon, 1973; Simon and Chase, 1973). Much of this time involves the development of pattern recognition skills that support the fluent identification of meaningful patterns of information plus knowledge of their implications for future outcomes (see Chapter 2). In all domains of learning, the development of

BOX 3.4 Finding the Area of a Figure

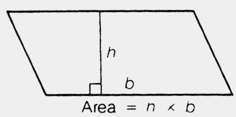
Understanding Method

The understanding method encouraged students to see the structural relations in the parallelogram, for example, that the parallelogram could be rearranged into a rectangle by moving a triangle from one side to the other. Since the students knew how to find the area of a rectangle, finding the area of a parallelogram was easy once they discovered the appropriate structural relations.



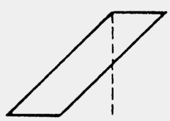
Rote Method

In the rote method, students were taught to drop a perpendicular and then apply the memorized solution formula.

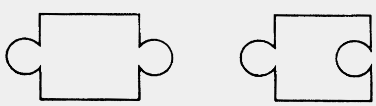


Transfer

Both groups performed well on typical problems asking for the area of parallelograms; however, only the understanding group could transfer to novel problems, such as finding the area of the figures below.



or distinguishing between solvable and unsolvable problems such as



The response of the "rote" group to novel problems was, "We haven't had that yet."

SOURCE: Based on Wertheimer (1959).

BOX 3.5 Learning Algebra

Students taking regular algebra in a major school system received an average of 65 hours of instruction and homework during the year. In contrast, those taking honors algebra received approximately 250 hours of instruction and homework (John Anderson, personal communication). Clearly, it was recognized that significant learning takes major investments of time.

expertise occurs only with major investments of time, and the amount of time it takes to learn material is roughly proportional to the amount of material being learned (Singley and Anderson, 1989); see Box 3.5. Although many people believe that "talent" plays a role in who becomes an expert in a particular area, even seemingly talented individuals require a great deal of practice in order to develop their expertise (Ericsson et al., 1993).

Learners, especially in school settings, are often faced with tasks that do not have apparent meaning or logic (Klausmeier, 1985). It can be difficult for them to learn with understanding at the start; they may need to take time to explore underlying concepts and to generate connections to other information they possess. Attempts to cover too many topics too quickly may hinder learning and subsequent transfer because students (a) learn only isolated sets of facts that are not organized and connected or (b) are introduced to organizing principles that they cannot grasp because they lack enough specific knowledge to make them meaningful. Providing students with opportunities to first grapple with specific information relevant to a topic has been shown to create a "time for telling" that enables them to learn much more from an organizing lecture (as measured by subsequent abilities to transfer) than students who did not first have these specific opportunities; see Box 3.6.

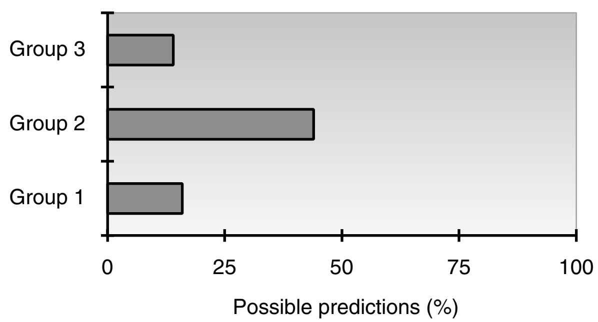
Providing students with time to learn also includes providing enough time for them to process information. Pezdek and Miceli (1982) found that on one particular task, it took 3rd graders 15 seconds to integrate pictorial and verbal information; when given only 8 seconds, they couldn't mentally integrate the information, probably due to short-term memory limitations. The implication is that learning cannot be rushed; the complex cognitive activity of information integration requires time.

Beyond "Time on Task"

It is clear that different ways of using one's time have different effects on learning and transfer. A considerable amount is known about variables that affect learning. For example, learning is most effective when people engage

BOX 3.6 Preparation for Learning with Understanding

Three different groups of college students received different kinds of instruction about schema theory and memory and then completed a transfer task where they were asked to make detailed predictions about the results of a new memory study. Students in Group 1 read and summarized a text on the topic of schema theory and then listened to a lecture designed to help them organize their knowledge and learn with understanding. Group 2 did not read the text but, instead, actively compared simplified data sets from schema experiments on memory and then heard the same lecture as Group 1. Group 3 spent twice as much time as Group 2 working with the data sets but did not receive the organizing lecture. On the transfer test, students in Group 2 performed much better than those in Groups 1 and 3. Their work with the data sets set the stage for them to learn from the lecture. The lecture was necessary, as indicated by the poor performance of Group 3.



SOURCE: From Schwartz et al. (1999).

in "deliberate practice" that includes active monitoring of one's learning experiences (Ericsson et al., 1993). Monitoring involves attempts to seek and use feedback about one's progress. Feedback has long been identified as important for successful learning (see, e.g., Thorndike, 1913), but it should not be regarded as a unidimensional concept. For example, feedback that signals progress in memorizing facts and formulas is different from feedback that signals the state of the students' understanding (Chi et al., 1989, 1994). In addition, as noted in Chapter 2, students need feedback about the degree to which they know when, where, and how to use the knowledge they are learning. By inadvertently relying on clues—such as which chapter in a text the practice problems came from—students can erroneously think they have conditionalized their knowledge when, in fact, they have not (Bransford, 1979).

Understanding when, where, and why to use new knowledge can be enhanced through the use of "contrasting cases," a concept from the field of perceptual learning (see, e.g., Gagné and Gibson, 1947; Garner, 1974; Gibson and Gibson, 1955). Appropriately arranged contrasts can help people notice new features that previously escaped their attention and learn which features are relevant or irrelevant to a particular concept. The benefits of appropriately arranged contrasting cases apply not only to perceptual learning, but also to conceptual learning (Bransford et al., 1989; Schwartz et al., 1999). For example, the concept of linear function becomes clearer when contrasted with nonlinear functions; the concept of recognition memory becomes clearer when contrasted with measures such as free recall and cued recall.

A number of studies converge on the conclusion that transfer is enhanced by helping students see potential transfer implications of what they are learning (Anderson et al., 1996). In one of the studies on learning LOGO programming (Klahr and Carver, 1988), the goal was to help students learn to generate "bug-free" instructions for others to follow. The researchers first conducted a careful task analysis of the important skills underlying the ability to program in LOGO and focused especially on LOGO debugging skills—the process by which children find and correct errors in their programs. Part of the researchers' success in teaching LOGO depended on this task analysis. The researchers identified the four key aspects of debugging a program as identifying the buggy behavior, representing the program, locating the bug in the program, and then correcting the bug. They highlighted these key abstract steps and signaled to the students that the steps would be relevant to the transfer task of writing debugging directions. Students who had LOGO training increased from 33 percent correct instructions to 55 percent correct instructions. They could have approached this task by memorizing the procedures for programming LOGO routines to "make a house," "make a polygon," and so forth. Simply memorizing the procedures, however, would not be expected to help students accomplish the transfer task of generating clear, bug-free instructions.

Motivation to Learn

Motivation affects the amount of time that people are willing to devote to learning. Humans are motivated to develop competence and to solve problems; they have, as White (1959) put it, "competence motivation." Although extrinsic rewards and punishments clearly affect behavior (see Chapter 1), people work hard for intrinsic reasons, as well.

Challenges, however, must be at the proper level of difficulty in order to be and to remain motivating: tasks that are too easy become boring; tasks that are too difficult cause frustration. In addition, learners' tendencies to persist in the face of difficulty are strongly affected by whether they are "performance oriented" or "learning oriented" (Dweck, 1989). Students who are learning oriented like new challenges; those who are performance oriented are more worried about making errors than about learning. Being learning oriented is similar to the concept of adaptive expertise discussed in Chapter 2. It is probable, but needs to be verified experimentally, that being "learning oriented" or "performance oriented" is not a stable trait of an individual but, instead, varies across disciplines (e.g., a person may be performance oriented in mathematics but learning oriented in science and social studies or vice versa).

Social opportunities also affect motivation. Feeling that one is contributing something to others appears to be especially motivating (Schwartz et al., 1999). For example, young learners are highly motivated to write stories and draw pictures that they can share with others. First graders in an inner-city school were so highly motivated to write books to be shared with others that the teachers had to make a rule: "No leaving recess early to go back to class to work on your book" (Cognition and Technology Group at Vanderbilt, 1998).

Learners of all ages are more motivated when they can see the usefulness of what they are learning and when they can use that information to do something that has an impact on others—especially their local community (McCombs, 1996; Pintrich and Schunk, 1996). Sixth graders in an inner-city school were asked to explain the highlights of their previous year in fifth grade to an anonymous interviewer, who asked them to describe anything that made them feel proud, successful, or creative (Barron et al., 1998). Students frequently mentioned projects that had strong social consequences, such as tutoring younger children, learning to make presentations to outside audiences, designing blueprints for playhouses that were to be built by professionals and then donated to preschool programs, and learning to work effectively in groups. Many of the activities mentioned by the students had involved a great deal of hard work on their part: for example, they had had to learn about geometry and architecture in order to get the chance to create blueprints for the playhouses, and they had had to explain their blueprints to a group of outside experts who held them to very high standards. (For other examples and discussions of highly motivating activities, see Pintrich and Schunk, 1996.)

OTHER FACTORS THAT INFLUENCE TRANSFER

Context

Transfer is also affected by the context of original learning; people can learn in one context, yet fail to transfer to other contexts. For example, a group of Orange County homemakers did very well at making supermarket best-buy calculations despite doing poorly on equivalent school-like paper-and-pencil mathematics problems (Lave, 1988). Similarly, some Brazilian street children could perform mathematics when making sales in the street but were unable to answer similar problems presented in a school context (Carraher, 1986; Carraher et al., 1985).

How tightly learning is tied to contexts depends on how the knowledge is acquired (Eich, 1985). Research has indicated that transfer across contexts is especially difficult when a subject is taught only in a single context rather than in multiple contexts (Bjork and Richardson-Klavhen, 1989). One frequently used teaching technique is to get learners to elaborate on the examples used during learning in order to facilitate retrieval at a later time. The practice, however, has the potential of actually making it more difficult to retrieve the lesson material in other contexts, because knowledge tends to be especially context-bound when learners elaborate the new material with details of the context in which the material is learned (Eich, 1985). When a subject is taught in multiple contexts, however, and includes examples that demonstrate wide application of what is being taught, people are more likely to abstract the relevant features of concepts and to develop a flexible representation of knowledge (Gick and Holyoak, 1983).

The problem of overly contextualized knowledge has been studied in instructional programs that use case-based and problem-based learning. In these programs, information is presented in a context of attempting to solve complex, realistic problems (e.g., Barrows, 1985; Cognition and Technology Group at Vanderbilt, 1997; Gragg, 1940; Hmelo, 1995; Williams, 1992). For example, fifth- and sixth-grade students may learn mathematical concepts of distance-rate-time in the context of solving a complex case involving planning for a boat trip. The findings indicate that if students learn only in this context, they often fail to transfer flexibly to new situations (Cognition and Technology Group at Vanderbilt, 1997). The issue is how to promote wide transfer of the learning.

One way to deal with lack of flexibility is to ask learners to solve a specific case and then provide them with an additional, similar case; the goal is to help them abstract general principles that lead to more flexible transfer (Gick and Holyoak, 1983); see Box 3.7. A second way to improve flexibility is to let students learn in a specific context and then help them engage in "what-if" problem solving designed to increase the flexibility of their understanding. They might be asked: "What if this part of the problem were changed, or this part?" (Cognition and Technology Group at Vanderbilt, 1997). A third way is to generalize the case so that learners are asked to create a solution that applies not simply to a single problem, but to a whole class of related problems. For example, instead of planning a single boat trip, students might run a trip planning company that has to advise people on travel times for different regions of the country. Learners are asked to adopt the goal of learning to "work smart" by creating mathematical models that characterize a variety of travel problems and using these models to create tools, ranging from simple tables and graphs to computer programs. Under these conditions, transfer to novel problems is enhanced (e.g., Bransford et al., 1998).

Problem Representations

Transfer is also enhanced by instruction that helps students represent problems at higher levels of abstraction. For example, students who create a specific business plan for a complex problem may not initially realize that their plan works well for "fixed-cost" situations but not for others. Helping students represent their solution strategies at a more general level can help them increase the probability of positive transfer and decrease the degree to which a previous solution strategy is used inappropriately (negative transfer).

Advantages of abstract problem representations have been studied in the context of algebra word problems involving mixtures. Some students were trained with pictures of the mixtures and other students were trained with abstract tabular representations that highlighted the underlying mathematical relationships (Singley and Anderson, 1989). Students who were trained on specific task components without being provided with the principles underlying the problems could do the specific tasks well, but they could not apply their learning to new problems. By contrast, the students who received abstract training showed transfer to new problems that involved *analogous* mathematical relations. Research has also shown that developing a suite of representations enables learners to think flexibly about complex domains (Spiro et al., 1991).

Relationships Between Learning and Transfer Conditions

Transfer is always a function of relationships between what is learned and what is tested. Many theorists argue that the amount of transfer will be a function of the overlap between the original domain of learning and the novel one. Measuring overlap requires a theory of how knowledge is represented and conceptually mapped across domains. Examples of research

BOX 3.7 Flexible Transfer

College students were presented with the following passage about a general and a fortress (Gick and Holyoak, 1980:309).

> A general wishes to capture a fortress located in the center of a country. There are many roads radiating outward from the fortress. All have been mined so that while small groups of men can pass over the roads safely, a large force will detonate the mines. A full-scale direct attack is therefore impossible. The general's solution is to divide his army into small groups, send each group to the head of a different road, and have the groups converge simultaneously on the fortress.

Students memorized the information in the passage and were then asked to try another task, which was to solve the following problem (Gick and Holyoak, 1980:307-308).

> You are a doctor faced with a patient who has a malignant tumor in his stomach. It is impossible to operate on the patient, but unless the tumor is destroyed the patient will die. There is a kind of ray that may be used to destroy the tumor. If the rays reach the tumor all at once and with sufficiently high intensity, the tumor will be destroyed, but surrounding tissue may be damaged as well. At lower intensities the rays are harmless to healthy tissue, but they will not affect the tumor either. What type of procedure might be used to destroy the tumor with the rays, and at the same time avoid destroying the healthy tissue?

Few college students were able to solve this problem when left to their own devices. However, over 90 percent were able to solve the tumor problem when they were explicitly told to use information about the general and the fortress to help them. These students perceived the analogy between dividing the troops into small units and using a number of small-dose rays that each converge on the same point—the cancerous tissue. Each ray is too weak to harm tissue except at the point of convergence. Despite the relevance of the fortress problem to the tumor problem, the information was not used spontaneously—the connection between the two sets of information had to be explicitly pointed out.

studies on conceptual representation include Brown (1986), Bassok and Holyoak (1989a, b), and Singley and Anderson (1989). Whether students will transfer across domains—such as distance formulas from physics to formally equivalent biological growth problems, for example—depends on whether they conceive of the growth as occurring continuously (successful transfer) or in discrete steps (unsuccessful transfer) (Bassok and Olseth, 1995).

Singley and Anderson (1989) argue that transfer between tasks is a function of the degree to which the tasks share *cognitive* elements. This hypothesis was also put forth very early in the development of research on transfer of identical elements, mentioned previously (Thorndike and Woodworth, 1901; Woodworth, 1938), but it was hard to test experimentally until there was a way to identify task components. In addition, modern theorists include cognitive representations and strategies as "elements" that vary across tasks (Singley and Anderson, 1989).

Singley and Anderson taught students several text editors, one after another, and sought to predict transfer, defined as the savings in time of learning a new editor when it was not taught first. They found that students learned subsequent text editors more rapidly and that the number of procedural elements shared by two text editors predicted the amount of this transfer. In fact, there was large transfer across editors that were very different in surface structures but that had common abstract structures. Singley and Anderson also found that similar principles govern transfer of mathematical competence across multiple domains when they considered transfer of declarative as well as procedural knowledge.

A study by Biederman and Shiffrar (1987) is a striking example of the benefits of abstract instruction. They studied a task that is typically difficult to learn in apprentice-like roles: how to examine day-old chicks to determine their sex. Biederman and Shiffrar found that twenty minutes of instruction on abstract principles helped the novices improve considerably (see also Anderson et al., 1996). Research studies generally provide strong support for the benefits of helping students represent their experiences at levels of abstraction that transcend the specificity of particular contexts and examples (National Research Council, 1994). Examples include algebra (Singley and Anderson, 1989), computer language tasks (Klahr and Carver, 1988), motor skills (e.g., dart throwing, Judd, 1908), analogical reasoning (Gick and Holyoak, 1983), and visual learning (e.g., sexing chicks, Biederman and Shiffrar, 1987).

Studies show that abstracted representations do not remain as isolated instances of events but become components of larger, related events, schemata (Holyoak, 1984; Novick and Holyoak, 1991). Knowledge representations are built up through many opportunities for observing similarities and differences across diverse events. Schemata are posited as particularly important guides to complex thinking, including analogical reasoning: "Successful analogical transfer leads to the induction of a general schema for the solved problems that can be applied to subsequent problems" (National Research Council, 1994:43). Memory retrieval and transfer are promoted by schemata because they derive from a broader scope of related instances than single learning experiences.

Active Versus Passive Approaches to Transfer

It is important to view transfer as a dynamic process that requires learners to actively choose and evaluate strategies, consider resources, and receive feedback. This active view of transfer is different from more static views, which assume that transfer is adequately reflected by learners' abilities to solve a set of transfer problems right after they have engaged in an initial learning task. These "one-shot" tests often seriously underestimate the amount of transfer that students display from one domain to another (Bransford and Schwartz, 1999; Brown et al., 1983; Bruer, 1993).

Studies of transfer from learning one text editor to another illustrate the importance of viewing transfer from a dynamic rather than a static perspective. Researchers have found much greater transfer to a second text editor on the *second* day of transfer than the first (Singley and Anderson, 1989): this finding suggests that transfer should be viewed as increased speed in learning a new domain—not simply initial performance. Similarly, one educational goal for a course in calculus is how it facilitates learning of physics, but not necessarily its benefit on the first day of physics class.

Ideally, an individual spontaneously transfers appropriate knowledge without a need for prompting. Sometimes, however, prompting is necessary. With prompting, transfer can improve quite dramatically (e.g., Gick and Holyoak, 1980; Perfetto et al., 1983). "The amount of transfer depends on where attention is directed during learning or at transfer" (Anderson et al., 1996:8).

An especially sensitive way to assess the degree to which students' learning has prepared them for transfer is to use methods of dynamic assessment, such as "graduated prompting" (Campione and Brown, 1987; Newman et al., 1989). This method can be used to assess the amount of help needed for transfer by counting the number and types of prompts that are necessary before students are able to transfer. Some learners can transfer after receiving a general prompt such as "Can you think of something you did earlier that might be relevant?" Other learners need prompts that are much more specific. Tests of transfer that use graduated prompting provide more fine-grained analysis of learning and its effects on transfer than simple one-shot assessments of whether or not transfer occurs.

Transfer and Metacognition

Transfer can be improved by helping students become more aware of themselves as learners who actively monitor their learning strategies and resources and assess their readiness for particular tests and performances. We briefly discussed the concept of metacognition in Chapters 1 and 3 (see Brown, 1975; Flavell, 1973). Metacognitive approaches to instruction have been shown to increase the degree to which students will transfer to new situations without the need for explicit prompting. The following examples illustrate research on teaching metacognitive skills across domains of reading, writing, and mathematics.

Reciprocal teaching to increase reading comprehension (Palincsar and Brown, 1984) is designed to help students acquire specific knowledge and also to learn a set of strategies for explicating, elaborating, and monitoring the understanding necessary for independent learning. The three major components of reciprocal teaching are instruction and practice with strategies that enable students to monitor their understanding; provision, initially by a teacher, of an expert model of metacognitive processes; and a social setting that enables joint negotiation for understanding. The knowledge-acquisition strategies the students learn in working on a specific text are not acquired as abstract memorized procedures, but as skills instrumental in achieving subject-area knowledge and understanding. The instructional procedure is reciprocal in the sense that a teacher and a group of students take turns in leading the group to discuss and use strategies for comprehending and remembering text content.

A program of procedural facilitation for teaching written composition (Scardamalia et al., 1984) shares many features with reciprocal teaching. The method prompts learners to adopt the metacognitive activities embedded in sophisticated writing strategies. The prompts help learners think about and reflect on the activities by getting them to identify goals, generate new ideas, improve and elaborate existing ideas, and strive for idea cohesion. Students in the procedural facilitation program take turns presenting their ideas to the group and detailing how they use prompts in planning to write. The teacher also models these procedures. Thus, the program involves modeling, scaffolding, and taking turns which are designed to help students externalize mental events in a collaborative context.

Alan Schoenfeld (1983, 1985, 1991) teaches heuristic methods for mathematical problem solving to college students. The methods are derived, to some extent, from the problem-solving heuristics of Polya (1957). Schoenfeld's program adopts methods similar to reciprocal teaching and procedural facilitation. He teaches and demonstrates control or managerial strategies and makes explicit such processes as generating alternative courses of action, evaluating which course one will be able to carry out and whether it can be managed in the time available, and assessing one's progress. Again, elements of modeling, coaching, and scaffolding, as well as collective problem solving and whole-class and small group discussions, are used. Gradually, students come to ask self-regulatory questions themselves as the teacher fades out. At the end of each of the problem-solving sessions, students and teacher alternate in characterizing major themes by analyzing what they did and why. The recapitulations highlight the generalizable features of the critical decisions and actions and focus on strategic levels rather than on the specific solutions (see also White and Frederickson, 1998).

An emphasis on metacognition can enhance many programs that use new technologies to introduce students to the inquiry methods and other tools that are used by professionals in the workplace (see Chapter 8). The important role of metacognition for learning has been demonstrated in the context of a "thinker tools" program that lets students run simulations of physics experiments (White and Frederickson, 1998), as well as in adding a metacognitive component to a computer program designed to help college students learn biology. The value of using video to model important metacognitive learning procedures has also been shown to help learners analyze and reflect on models (Bielaczyc et al., 1995). All of these strategies engage learners as active participants in their learning by focusing their attention on critical elements, encouraging abstraction of common themes or procedures (principles), and evaluating their own progress toward understanding.

LEARNING AS TRANSFER FROM PREVIOUS EXPERIENCES

When people think about transfer, it is common to think first about learning something and then assessing the learner's abilities to apply it to something else. But even the initial learning phase involves transfer because it is based on the knowledge that people bring to any learning situation; see Box 3.8. The principle that people learn by using what they know to construct new understandings (see Chapter 1) can be paraphrased as "all learning involves transfer from previous experiences." This principle has a number of important implications for educational practice. First, students may have knowledge that is relevant to a learning situation that is not activated. By helping activate this knowledge, teachers can build on students' strengths. Second, students may misinterpret new information because of previous knowledge they use to construct new understandings. Third, students may have difficulty with particular school teaching practices that conflict with practices in their community. This section discusses these three implications.

BOX 3.8 Everyday and Formal Math

The importance of building on previous experiences is relevant for adults as well as children. A mathematics instructor describes his realization of his mother's knowledge (Fasheh, 1990:21-22):

> Math was necessary for my mother in a much more profound and real sense than it was for me. Unable to read or write, my mother routinely took rectangles of fabric and, with new measurements and no patterns, cut them and turned them into perfectly fitted clothing for people . . . I realized that the mathematics she was using was beyond my comprehension. Moreover, although mathematics was a subject matter that I studied and taught, for her it was basic to the operation of her understanding. What she was doing was math in the sense that it embodied order, pattern, relations, and measurement. It was math because she was breaking a whole into smaller parts and constructing a new whole out of most of the pieces, a new whole that had its own style, shape, size, and that had to fit a specific person. Mistakes in her math entailed practical consequences, unlike mistakes in my math.

Imagine Fasheh's mother enrolling in a course on formal mathematics. The structure of many courses would fail to provide the kinds of support that could help her make contact with her rich set of informal knowledge. Would the mother's learning of formal mathematics be enhanced if it were connected to this knowledge? The literature on learning and transfer suggests that this is an important question to pursue.

Building on Existing Knowledge

Children's early mathematics knowledge illustrates the benefits of helping students draw on relevant knowledge that can serve as a source of transfer. By the time children begin school, most have built a considerable knowledge store relevant to arithmetic. They have experiences of adding and subtracting numbers of items in their everyday play, although they lack the symbolic representations of addition and subtraction that are taught in school. If children's knowledge is tapped and built on as teachers attempt to teach them the formal operations of addition and subtraction, it is likely that children will acquire a more coherent and thorough understanding of these processes than if they taught them as isolated abstractions. Without specific guidance from teachers, students may fail to connect everyday knowledge to subjects taught in school.

Understanding Conceptual Change

Because learning involves transfer from previous experiences, one's existing knowledge can also make it difficult to learn new information. Sometimes new information will seem incomprehensible to students, but this feeling of confusion can at least let them identify the existence of a problem (see, e.g., Bransford and Johnson, 1972; Dooling and Lachman, 1971). A more problematic situation occurs when people construct a coherent (for them) representation of information while deeply misunderstanding the new information. Under these conditions, the learner doesn't realize that he or she is failing to understand. Two examples of this phenomenon are in Chapter 1: *Fish Is Fish* (Lionni, 1970), where the fish listens to the frog's descriptions of people and constructs its own idiosyncratic images, and attempts to help children learn that the earth is spherical (Vosniadou and Brewer, 1989). Children's interpretations of the new information are much different than what adults intend.

The *Fish Is Fish* scenario is relevant to many additional attempts to help students learn new information. For example, when high school or college physics students are asked to identify the forces being exerted on a ball that is thrown vertically up in the air after it leaves the hand, many mention the "force of the hand" (Clement, 1982a, b). This force is exerted only so long as the ball is in contact with the hand, but is not present when the ball is in flight. Students claim that this force diminishes as the ball ascends and is used up by the time the ball reaches the top of its trajectory. As the ball descends, these students claim, it "acquires" increasing amounts of the gravitational force, which results in the ball picking up speed as it falls back down. This "motion requires a force" misconception is quite common among students and is akin to the medieval theory of "impetus" (Hestenes et al., 1992). These explanations fail to take account of the fact that the only forces being exerted on the ball while it is traveling through the air are the gravitational force caused by the earth and the drag force due to air resistance. (For similar examples, see Mestre, 1994.)

In biology, people's knowledge of human and animal needs for food provides an example of how existing knowledge can make it difficult to understand new information. A study of how plants make food was conducted with students from elementary school through college. It probed understanding of the role of soil and photosynthesis in plant growth and of the primary source of food in green plants (Wandersee, 1983). Although students in the higher grades displayed a better understanding, students from all levels displayed several misconceptions: soil is the plants' food; plants get their food from the roots and store it in the leaves; and chlorophyll is the plants' blood. Many of the students in this study, especially those in the higher grades, had already studied photosynthesis. Yet formal instruction had done little to overcome their erroneous prior beliefs. Clearly, presenting a sophisticated explanation in science class, without also probing for students' preconceptions on the subject, will leave many students with incorrect understanding (for a review of studies, see Mestre, 1994).

For young children, early concepts in mathematics guide students' attention and thinking (Gelman, 1967; we discuss this more in Chapter 4). Most children bring to their school mathematics lessons the idea that numbers are grounded in the counting principles (and related rules of addition and subtraction). This knowledge works well during the early years of schooling. However, once students are introduced to rational numbers, their assumptions about mathematics can hurt their abilities to learn.

Consider learning about fractions. The mathematical principles underlying the numberhood of fractions are not consistent with the principles of counting and children's ideas that numbers are sets of things that are counted and addition involves "putting together" two sets. One cannot count things to generate a fraction. Formally, a fraction is defined as the division of one cardinal number by another: this definition solves the problem that there is a lack of closure of the integers under division. To complicate matters, some number-counting principles do not apply to fractions. Rational numbers do not have unique successors; there is an infinite number of numbers between any two rational numbers. One cannot use counting-based algorithms for sequencing fractions: for example, 1/4 is not more than 1/2. Neither the nonverbal nor the verbal counting principle maps to a tripartite symbolic representations of fractions—two cardinal numbers X and Y separated by a line. Related mapping problems have been noted by others (e.g., Behr et al., 1992; Fishbein et al., 1985; Silver et al., 1993). Overall, early knowledge of numbers has the potential to serve as a barrier to learning about fractions—and for many learners it does.

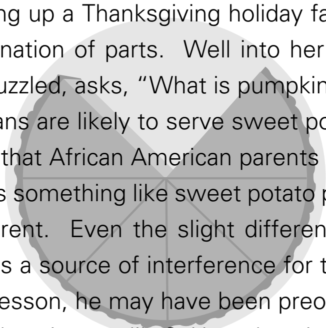
The fact that learners construct new understandings based on their current knowledge highlights some of the dangers in "teaching by telling." Lectures and other forms of direct instruction can sometimes be very useful, but only under the right conditions (Schwartz and Bransford, 1998). Often, students construct understandings like those noted above. To counteract these problems, teachers must strive to make students' thinking visible and find ways to help them reconceptualize faulty conceptions. (Strategies for such teaching are discussed in more detail in Chapters 6 and 7.)

Transfer and Cultural Practices

Prior knowledge is not simply the individual learning that students bring to the classroom, based on their personal and idiosyncratic experiences (e.g., some children will know many things because they have traveled widely or because their parents have particular kinds of jobs; some children may have suffered a traumatic experience). Prior knowledge is also not only a generic set of experiences attributable to developmental stages through which learners may have passed (i.e., believing that heaven is "up" or that milk comes from refrigerated cartons). Prior knowledge also includes the kind of knowledge that learners acquire because of their social roles, such as those connected with race, class, gender, and their culture and ethnic affiliations (Brice-Heath, 1981, 1983; Lave, 1988; Moll and Whitmore, 1993; Moll et al., 1993-1998; Rogoff, 1990, 1998; Saxe, 1990). This cultural knowledge can sometimes support and sometimes conflict with children's learning in schools (Greenfield and Suzuki, 1998); see Box 3.9.

School failure may be partly explained by the mismatch between what students have learned in their home cultures and what is required of them in school (see Allen and Boykin, 1992; Au and Jordan, 1981; Boykin and Tom, 1985; Erickson and Mohatt, 1982). Everyday family habits and rituals can either be reinforced or ignored in schools, and they can produce different responses from teachers (Heath, 1983). For example, if young learners are never asked questions at home that seem obvious to some families—such as "What color is the sky?" or "Where is your nose?"—teachers who ask such questions may find students reluctant or resistant to answer. How teachers interpret this reticence or resistance has consequences for how intelligent or academically capable they judge students and their instructional approaches toward them.

BOX 3.9 Eating Pie and Learning Fractions



Even small differences in cultural knowledge have the potential to affect students' learning. For example, a primary school teacher is helping students to understand fractional parts by using what she thinks is a commonplace reference. "Today, we're going to talk about cutting up a Thanksgiving holiday favorite—pumpkin pie." She continues with an explanation of parts. Well into her discourse, a young African American boy, looking puzzled, asks, "What is pumpkin pie?" (Tate, 1994).

Most African Americans are likely to serve sweet potato pie for holiday dinners. In fact, one of the ways that African American parents explain pumpkin pie to their children is to say that it is something like sweet potato pie. For them, sweet potato pie is the common referent. Even the slight difference of being unfamiliar with pumpkin pie can serve as a source of interference for the student. Rather than be engaged actively in the lesson, he may have been preoccupied with trying to imagine pumpkin pie: What does it taste like? How does it smell? Is its texture chunky like apple or cherry pie? In the mind of a child, all of these questions can become more of the focus than the subject of fractions that the teacher is attempting to teach.

These differences have their roots in early adult-infant interactions (Blake, 1994). Whereas middle-class Anglo mothers tend to have frequent language interactions that are focused on didactic naming and pointing with their infants around objects ("Look at that red truck!"), African American mothers show comparable frequency levels of language interactions with their infants, but focused on affective dimensions of language ("Isn't that a pretty toy? Doesn't it make you feel happy?"). The language that children bring with them to school involves a broad set of skills rooted in the early context of adult-child interactions. What happens when the adults, peers, and contexts change (Suina, 1988; Suina and Smolkin, 1994)? This is an important question that relates to the transfer of learning.

The meanings that are attached to cultural knowledge are important in promoting transfer—that is, in encouraging people to use what they have learned. For example, story-telling is a language skill. Topic-associative oral styles have been observed among African American children (Michaels, 1981a,b; 1986). In contrast, white children use a more linear narrative style that more closely approximates the linear expository style of writing and speaking that schools teach (see Gee, 1989; Taylor and Lee, 1987; Cazden et al., 1985; Lee and Slaughter-Defoe, 1995). Judgments may be made by white and black teachers as they listen to these two language styles: white teachers find the topic-associative stories hard to follow and are much more likely to infer that the narrator is a low-achieving student; black teachers are more likely to positively evaluate the topic-associative style (Cazden, 1988:17). African American children who come to school speaking in a topic-associative style may be seen by many teachers as having less potential for learning. Teachers can be helped to view different cultural backgrounds as strengths to be built on, rather than as signs of "deficits."

TRANSFER BETWEEN SCHOOL AND EVERYDAY LIFE

We began this chapter by stressing that the ultimate goal of learning is to have access to information for a wide set of purposes—that the learning will in some way transfer to other circumstances. In this sense, then, the ultimate goal of schooling is to help students transfer what they have learned in school to everyday settings of home, community, and workplace. Since transfer between tasks is a function of the similarity by transfer tasks and learning experiences, an important strategy for enhancing transfer from schools to other settings may be to better understand the nonschool environments in which students must function. Since these environments change rapidly, it is also important to explore ways to help students develop the characteristics of adaptive expertise (see Chapter 1).

The question of how people function in a number of practical settings has been examined by many scientists, including cognitive anthropologists, sociologists, and psychologists (e.g., Lave, 1988; Rogoff, 1990). One major contrast between everyday settings and school environments is that the latter place much more emphasis on individual work than most other environments (Resnick, 1987). A study of navigation on U.S. ships found that no individual can pilot the ship alone; people must work collaboratively and share their expertise. More recent studies of collaboration confirm its importance. For example, many scientific discoveries in several genetics laboratories involve in-depth collaboration (Dunbar, 1996). Similarly, decision making in hospital emergency rooms is distributed among many different members of the medical team (Patel et al., 1996).

A second major contrast between schools and everyday settings is the heavy use of tools to solve problems in everyday settings, compared with "mental work" in school settings (Resnick, 1987). The use of tools in practical environments helps people work almost error free (e.g., Cohen, 1983; Schliemann and Acioly, 1989; Simon, 1972; see also Norman, 1993). New technologies make it possible for students in schools to use tools very much like those used by professionals in workplaces (see Chapter 8). Proficiency with relevant tools may provide a way to enhance transfer across domains.

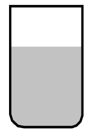
A third contrast between schools and everyday environments is that abstract reasoning is often emphasized in school, whereas contextualized reasoning is often used in everyday settings (Resnick, 1987). Reasoning can be improved when abstract logical arguments are embodied in concrete contexts (see Wason and Johnson-Laird, 1972). A well-known study of people in a Weight Watchers program provides similar insights into everyday problem solving (see Lave et al., 1984). One example is of a man who needed three-fourths of two-thirds of a cup of cottage cheese to create a dish he was cooking. He did not attempt to multiply the fractions as students would do in a school context. Instead, he measured two-thirds of a cup of cottage cheese, removed that amount from the measuring cup and then patted the cheese into a round shape, divided it into quarters, and used three of the quarters; see Box 3.10. Abstract arithmetic was never used. In similar examples of contextualized reasoning, dairy workers use knowledge, such as the size of milk cases, to make their computational work more efficient (Scribner, 1984); grocery store shoppers use nonschool mathematics under standard supermarket and simulated conditions (Lave, 1988); see Box 3.11.

There are potential problems with contextualized reasoning, which are similar to those associated with overly contextualized knowledge in general. The "pat it out" strategy used for cottage cheese works in only a narrow range of situations; the man would have difficulty if he were trying to measure molasses or other liquids rather than cottage cheese (Wineburg, 1989a, b; see also Bereiter, 1997). Could he generate a new strategy for molasses or other liquids? The answer to this question depends on the degree to which he can relate his procedure to more general sets of solution strategies.

BOX 3.10 The Cottage Cheese Problem

How can you get 3/4 of 2/3 cup of cottage cheese?

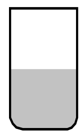
3/4 of



School Mathematics Strategy

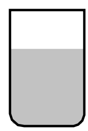
3/4 x 2/3 = 6/12 = 1/2 cup

Fill a cup to the 1/2 mark with cottage cheese.

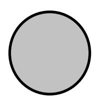


Invented Strategy

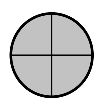
Fill a cup to 2/3 marking.



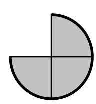
Pour out contents and form a circle.



Cut the circle into four equal parts.



Take away one part and use the rest.

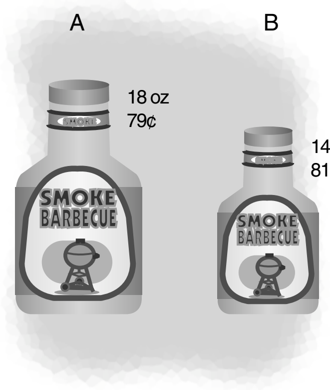


BOX 3.11 Three Solutions to the Best-Buy Problem

	Percentage Using Strategy	
	Simulation study	Supermarket study
Which is the best buy for barbecue sauce? ***Difference strategy*** — 18 – 14 = 4 ounces; 79 – 81 = –2 cents; A gives 4 more ounces and costs 2 cents less than B	***9***	***22***
Which is the best buy for sunflower seeds? ***Unit-price strategy*** — 30/3 = 10 cents per ounce; 44/4 = 11 cents per ounce; A costs less per ounce than B	***39***	***5***
Which is the best buy for peanuts? ***Ratio strategy*** — 2 × 45 = 90 cents; 2 × 4 = 8 ounces; A costs twice as much as B and contains more than twice as much	***47***	***35***

Which is the best buy for barbecue sauce?

Difference strategy

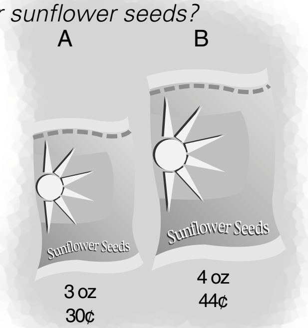


18 – 14 = 4 ounces
79 – 81 = –2 cents
A gives 4 more ounces and costs 2 cents less than B

Which is the best buy for sunflower seeds?

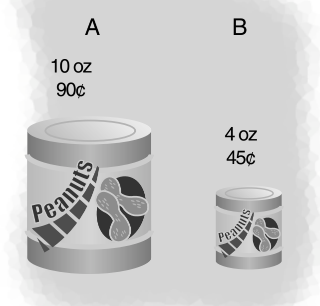
Unit-price strategy

30/3 = 10 cents per ounce
44/4 = 11 cents per ounce
A costs less per ounce than B



Which is the best buy for peanuts?

Ratio strategy



2 × 45 = 90 cents
2 × 4 = 8 ounces
A costs twice as much as B and contains more than twice as much

SOURCE: Adapted from Lave (1988).

Analyses of everyday environments have potential implications for education that are intriguing but need to be thought through and researched carefully. There are many appealing strengths to the idea that learning should be organized around authentic problems and projects that are frequently encountered in nonschool settings: in John Dewey's vision, "School should be less about preparation for life and more like life itself." The use of problem-based learning in medical schools is an excellent example of the benefits of looking at what people need to do once they graduate and then crafting educational experiences that best prepare them for these competencies (Barrows, 1985). Opportunities to engage in problem-based learning during the first year of medical school lead to a greater ability to diagnose and understand medical problems than do opportunities to learn in typical lecture-based medical courses (Hmelo, 1995). Attempts to make schooling more relevant to the subsequent workplace have also guided the use of case-based learning in business schools, law schools, and schools that teach educational leadership (Hallinger et al., 1993; Williams, 1992).

The transfer literature also highlights some of the potential limitations of learning in particular contexts. Simply learning to perform procedures, and learning in only a single context, does not promote flexible transfer. The transfer literature suggests that the most effective transfer may come from a balance of specific examples and general principles, not from either one alone.

SUMMARY AND CONCLUSION

A major goal of schooling is to prepare students for flexible adaptation to new problems and settings. The ability of students to transfer provides an important index of learning that can help teachers evaluate and improve their instruction. Many approaches to instruction look equivalent when the only measure of learning is memory for information that was specifically presented. Instructional differences become more apparent when evaluated from the perspective of how well the learning transfers to new problems and settings.

Several critical features of learning affect people's abilities to transfer what they have learned. The amount and kind of initial learning is a key determinant of the development of expertise and the ability to transfer knowledge. Students are motivated to spend the time needed to learn complex subjects and to solve problems that they find interesting. Opportunities to use knowledge to create products and benefits for others are particularly motivating for students.

While time on task is necessary for learning, it is not sufficient for effective learning. Time spent learning for understanding has different consequences for transfer than time spent simply memorizing facts or procedures from textbooks or lectures. In order for learners to gain insight into their learning and their understanding, frequent feedback is critical: students need to monitor their learning and actively evaluate their strategies and their current levels of understanding.

The context in which one learns is also important for promoting transfer. Knowledge that is taught in only a single context is less likely to support flexible transfer than knowledge that is taught in multiple contexts. With multiple contexts, students are more likely to abstract the relevant features of concepts and develop a more flexible representation of knowledge. The use of well-chosen contrasting cases can help students learn the conditions under which new knowledge is applicable. Abstract representations of problems can also facilitate transfer. Transfer between tasks is related to the degree to which they share common elements, although the concept of elements must be defined cognitively. In assessing learning, the key is increased speed of learning the concepts underlying the new material, rather than early performance attempts in a new subject domain.

All new learning involves transfer. Previous knowledge can help or hinder the understanding of new information. For example, knowledge of everyday counting-based arithmetic can make it difficult to deal with rational numbers; assumptions based on everyday physical experiences (e.g., walking upright on a seemingly flat earth) can make it difficult for learners to understand concepts in astronomy and physics and so forth. Teachers can help students change their original conceptions by helping students make their thinking visible so that misconceptions can be corrected and so that students can be encouraged to think beyond the specific problem or to think about variations on the problem. One aspect of previous knowledge that is extremely important for understanding learning is cultural practices that support learners' prior knowledge. Effective teaching supports positive transfer by actively identifying the relevant knowledge and strengths that students bring to a learning situation and building on them.

Transfer from school to everyday environments is the ultimate purpose of school-based learning. An analysis of everyday environments provides opportunities to rethink school practices in order to bring them into alignment with the requirements of everyday environments. But it is important to avoid instruction that is overly dependent on context. Helping learners choose, adapt, and invent tools for solving problems is one way to facilitate transfer while also encouraging flexibility.

Finally, a metacognative approach to teaching can increase transfer by helping students learn about themselves as learners in the context of acquiring content knowledge. One characteristic of experts is an ability to monitor and regulate their own understanding in ways that allows them to keep learning adaptive expertise: this is an important model for students to emulate.

4

How Children Learn

Children differ from adult learners in many ways, but there are also surprising commonalities across learners of all ages. In this chapter we provide some insights into children as learners. A study of young children fulfills two purposes: it illustrates the strengths and weaknesses of the learners who populate the nation's schools, and it offers a window into the development of learning that cannot be seen if one considers only well-established learning patterns and expertise. In studying the development of children, an observer gets a dynamic picture of learning unfolding over time. A fresh understanding of infant cognition and of how young children from 2 to 5 years old build on that early start also sheds new light on how to ease their transition into formal school settings.

INFANTS' CAPABILITIES

Theories

It was once commonly thought that infants lack the ability to form complex ideas. For much of this century, most psychologists accepted the traditional thesis that a newborn's mind is a blank slate (*tabula rasa*) on which the record of experience is gradually impressed. It was further thought that language is an obvious prerequisite for abstract thought and that, in its absence, a baby could not have knowledge. Since babies are born with a limited repertoire of behaviors and spend most of their early months asleep, they certainly appear passive and unknowing. Until recently, there was no obvious way for them to demonstrate otherwise.

But challenges to this view arose. It became clear that with carefully designed methods, one could find ways to pose rather complex questions about what infants and young children know and can do. Armed with new methodologies, psychologists began to accumulate a substantial body of data about the remarkable abilities that young children possess that stands in stark contrast to the older emphases on what they lacked. It is now known that very young children are competent, active agents of their own conceptual development. In short, the mind of the young child has come to life (Bruner, 1972, 1981a, b; Carey and Gelman, 1991; Gardner, 1991; Gelman and Brown, 1986; Wellman and Gelman, 1992).

A major move away from the *tabula rasa* view of the infant mind was taken by the Swiss psychologist Jean Piaget. Beginning in the 1920s, Piaget argued that the young human mind can best be described in terms of complex cognitive structures. From close observations of infants and careful questioning of children, he concluded that cognitive development proceeds through certain stages, each involving radically different cognitive schemes.

While Piaget observed that infants actually seek environmental stimulation that promotes their intellectual development, he thought that their initial representations of objects, space, time, causality, and self are constructed only gradually during the first 2 years. He concluded that the world of young infants is an egocentric fusion of the internal and external worlds and that the development of an accurate representation of physical reality depends on the gradual coordination of schemes of looking, listening, and touching.

After Piaget, others studied how newborns begin to integrate sight and sound and explore their perceptual worlds. For perceptual learning theorists, learning was considered to proceed rapidly due to the initial availability of exploration patterns that infants use to obtain information about the objects and events of their perceptual worlds (Gibson, 1969). As information processing theories began to emerge, the metaphor of mind as computer, information processor, and problem solver came into wide usage (Newell et al., 1958) and was quickly applied to the study of cognitive development.

Although these theories differed in important ways, they shared an emphasis on considering children as active learners who are able to set goals, plan, and revise. Children are seen as learners who assemble and organize material. As such, cognitive development involves the acquisition of organized knowledge structures including, for example, biological concepts, early number sense, and early understanding of basic physics. In addition, cognitive development involves the gradual acquisition of strategies for remembering, understanding, and solving problems.

The active role of learners was also emphasized by Vygotsky (1978), who pointed to other supports for learning. Vygotsky was deeply interested in the role of the social environment, included tools and cultural objects, as well as people, as agents in developing thinking. Perhaps the most powerful idea from Vygotsky to influence developmental psychology was that of a *zone of proximal development* (Vygotsky, 1978), described in Box 4.1. It refers to a bandwidth of competence (Brown and Reeve, 1987) that learners can navigate with aid from a supportive context, including the assistance of others. (For modern treatments of this concept, see Newman et al., 1989;

BOX 4.1 Zone of Proximal Development

The zone of proximal development is the distance between the actual developmental level as determined by independent problem solving and the level of potential development as determined through problem solving under adult guidance, or in collaboration with more capable peers (Vygotsky, 1978:86). What children can do with the assistance of others is even more indicative of their mental development than what they can do alone (Vygotsky, 1978:85).

The zone of proximal development embodies a concept of readiness to learn that emphasizes upper levels of competence. These upper boundaries are not immutable, however, but constantly changing with the learner's increasing independent competence. What a child can perform today with assistance she will be able to perform tomorrow independently, thus preparing her for entry into a new and more demanding collaboration. These functions could be called the "buds," rather than the fruits of development. The actual developmental level characterizes mental development retrospectively, while the zone of proximal development characterizes mental development prospectively (Vygotsky, 1978:86-87).

Moll and Whitmore, 1993; Rogoff and Wertsch, 1984; from a different theoretical perspective, see Bidell and Fischer, 1997.) This line of work has drawn attention to the roles of more capable peers, parents, and other partners in challenging and extending children's efforts to understand. It has also contributed to an understanding of the relationship between formal and informal teaching and learning situations (Lave and Wenger, 1991) and cognition distributed across people and tools (Salomon, 1993).

As a result of these theoretical and methodological developments, great strides have been made in studying young children's learning capacities. To summarize an enormous body of research, there have been dramatic increases in knowledge in four major areas of research, illustrated in this chapter:

1. *Early predisposition to learn about some things but not others* No evidence exists that infants come into the world as "blank slates" capable only of registering the ambient events that impinge on their senses in an undisciplined way. Young children show positive biases to learn types of information readily and early in life. These forms of knowledge, referred to as *privileged domains*, center on broadly defined categories, notably physi-

cal and biological concepts, causality, number, and language (Carey and Gelman, 1991).

2. *Strategies and metacognition* Outside of these privileged domains children, like all learners, must depend on will, ingenuity, and effort to enhance their learning. It was previously thought that young children lacked the strategic competence and knowledge about learning (metacognition) to learn intentionally, but the last 30 years have witnessed a great deal of research that reveals hitherto unrecognized strategic and metacognitive competence in the young (Brown and DeLoache, 1978; DeLoache et al., 1998).

3. *Theories of mind* As they mature, children develop theories of what it means to learn and understand that profoundly influence how they situate themselves in settings that demand effortful and intentional learning (Bereiter and Scardamalia, 1989). Children entertain various theories of mind and intelligence (Dweck and Legget, 1988). Indeed, not all learners in schools come ready to learn in exactly the same way. Some theorists argue that there is more than one way to learn, more than one way to be "intelligent." Understanding that there are multiple intelligences (Gardner, 1983) may suggest ways of helping children learn by supporting their strengths and working with their weakenesses.

4. *Children and community* Although a great deal of children's learning is self-motivated and self-directed, other people play major roles as guides in fostering the development of learning in children. Such guides include other children as well as adults (caretakers, parents, teachers, coaches, etc.). But not only people can serve as guides; so, too, can powerful tools and cultural artifacts, notably television, books, videos, and technological devices of many kinds (Wright and Huston, 1995). A great deal of research on such assisted learning has been influenced by Vygotsky's notion of zones of proximal development and the increasing popularity of the concept of "communities of learners," be they face-to-face or through electronic media and technologies (see Chapters 8 and 9).

Methodological Advances

The large increase in the number of studies that address early learning came about as a result of methodological advances in the field of developmental psychology. Much of what is now known about the human mind comes from the study of how infants learn. This work demonstrates that the human mind is a biologically prepared organism (Carey and Gelman, 1991). In order to study what babies know and can learn about readily, researchers needed to develop techniques of "asking" infants, who cannot speak, what they know. Because infants are so limited physically, experimenters interested in finding out how babies think had to find methods suitable to an infant's motor capabilities. New ways were developed for measuring what infants prefer to look at (Fantz, 1961) and detecting changes in events to which they are sensitive. Three such methods are non-nutritive sucking, habituation, and visual expectation.

Non-nutritive sucking is a way to use a physical capability that even the youngest infants have. In one experiment, the researchers (Kalnins and Bruner, 1973) showed 5- to 12-week-old infants a silent color film and gave the infants a pacifier to suck, the nipple of which was connected to a pressure switch that controlled the projector lens. The infants quickly learned to suck at a given rate to bring the movie into focus, showing not only that they were capable of and interested in learning how to control their own sensory environment, but also that they preferred a clear image to a blurry one.

The second method demonstrates an infant's thirst for novelty. The habituation paradigm involves presenting babies with an event (a stimulus)—a picture, sound, or series of sounds—to which the baby attends either by looking at it, turning to it, or doing something to keep the event continuing. Over a period of time infants stop responding to repeated presentations of the same event: that is, they *habituate*. They recover interest if a recognizably different event is presented. A combination of non-nutritive sucking and habituation was used in a study (Eimas et al., 1971) to show that 4-month-old infants will suck vigorously when first introduced to the phoneme (speech sound) "ba," then gradually lose interest and stop sucking. But when presented with a different phoneme, "pa," they resume sucking.

Because infants will look at things they find interesting, researchers developed the method of visual expectation to study infants' comprehension of events. It uses infants' gaze patterns to determine if they are comprehending patterns of visual events. For example, an experimenter establishes a pattern of flashing a picture two times on the left side of a screen and then three times on the right side. Once this alternating pattern has been established, the experimenter can watch an infant's gaze while the pictures continue to be flashed. If the baby continues to gaze at the left side of the screen after one flash, but then shifts its gaze to the right side after the second picture appears, then it is assumed that a distinction has been made between one, two, and three events. Using this procedure, infants as young as 5 months have shown that they can count up to three (Canfield and Smith, 1996).

Thus, using infants' capacities for looking, sucking, and interest in novelty, developmental psychologists devised methods for reliably studying early aspects of infant cognition. These studies have been refined for studying early infant memory development by using bodily actions, such as leg kicking and arm movements, for determining object recognition (Rovee-Collier, 1989).

Studies like these do more than simply show that infants actively select experiences; they also demonstrate what infants are capable of perceiving, knowing, and remembering. Recovery of interest in a novel speech sound could only occur if infants could recognize the rather subtle difference between "pa" and "ba." Discovering that very young infants can see, hear, smell, and be particular about what exactly they wish to explore led to an emboldened attitude about the kinds of experimental questions that could be asked. The answers about infant understanding of physical and biological causality, number, and language have been quite remarkable. These studies have profoundly altered scientific understanding of how and when humans begin to grasp the complexities of their worlds. In the next section, we present a few examples of infants' learning in these domains.

EARLY COMPETENCIES IN THE PRIVILEGED DOMAINS

Physical Concepts

How do infants learn about the physical world? Research studies have demonstrated that infants as early as 3-4 months of age have the beginnings of useful knowledge. Three examples from many: they understand that objects need support to prevent them from falling; that stationary objects are displaced when they come into contact with moving objects; and that inanimate objects need to be propelled into motion.

Consider the notion of support—that an object cannot be suspended in mid-air. In one study, infants are seated in front of a table that includes a platform. They see an experimenter's gloved hand reach out from a side window and put a box on top of the platform (possible event) and then withdraw her hand. Alternatively, when the experimenter reaches out from the side window, she places the box beyond the platform, leaving the impression that the box is suspended in mid-air when she withdraws her hand (impossible condition); see Figure 4.1.

Using the visual habituation methodology, studies have found that infants as young as 3 months old look reliably longer at the impossible events. This reaction indicates that infants *expect* that a box can be stable when a hand releases it onto a platform, but not when there is no supporting platform (Baillargeon et al., 1992; Needham and Baillargeon, 1993; Kolstad and Baillargeon, 1994); see Figure 4.2.

In a study of visual fixation on consistent and inconsistent events with light and heavy objects, Schilling and Clifton (1998) also showed that 9-month-old infants look longer at the physically inconsistent events than those that are consistent with their expectations; see Figure 4.3. Another well-documented example of infants' early understanding of physical causality is that stationary objects are displaced when hit by moving objects. Research studies have demonstrated that infants as young as 2-1/2 months understand

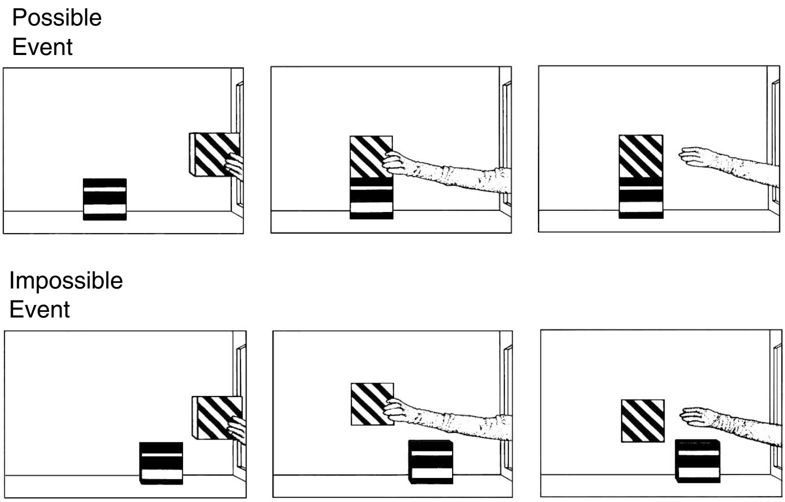


FIGURE 4.1 *Testing infants' understanding of possible and impossible physical events. SOURCE: Test events used in Needham and Baillargeon (1993).*

this concept, though it is not until about 6-1/2 months of age that they relate the size of the moving object and the distance of displacement of the stationary objects. "When looking at collision events between a moving and a stationary object, infants first form an initial concept centered on an impact/no-impact decision. With further experience, infants begin to identify variables that influence this initial concept" (Baillargeon, 1995:193).

In the first year of life, infants can understand that inanimate objects need to be propelled into action, that the objects cannot move themselves. For example, Leslie (1994a,b) showed that 4- to 7-month-old infants expect a point of contact to be involved in physical displacement. In one study, the infant watches a film in which a hand approaches a stationary doll and either appears to pick it up (contact condition) and moves away or the doll moves in tandem but without physical contact (no-contact condition). Using the habituation methodology, Leslie demonstrated that infants are highly sensitive to spatiotemporal discontinuities: they see the hand as an agent to cause movement in an inanimate object, but the no-contact conditions are seen as anomalous events—violations of causal principles.

The early understandings just described are soon reflected in children's spontaneous actions. In studies of his own young children's exploratory play, Piaget found that by 12 months of age they clearly understood the

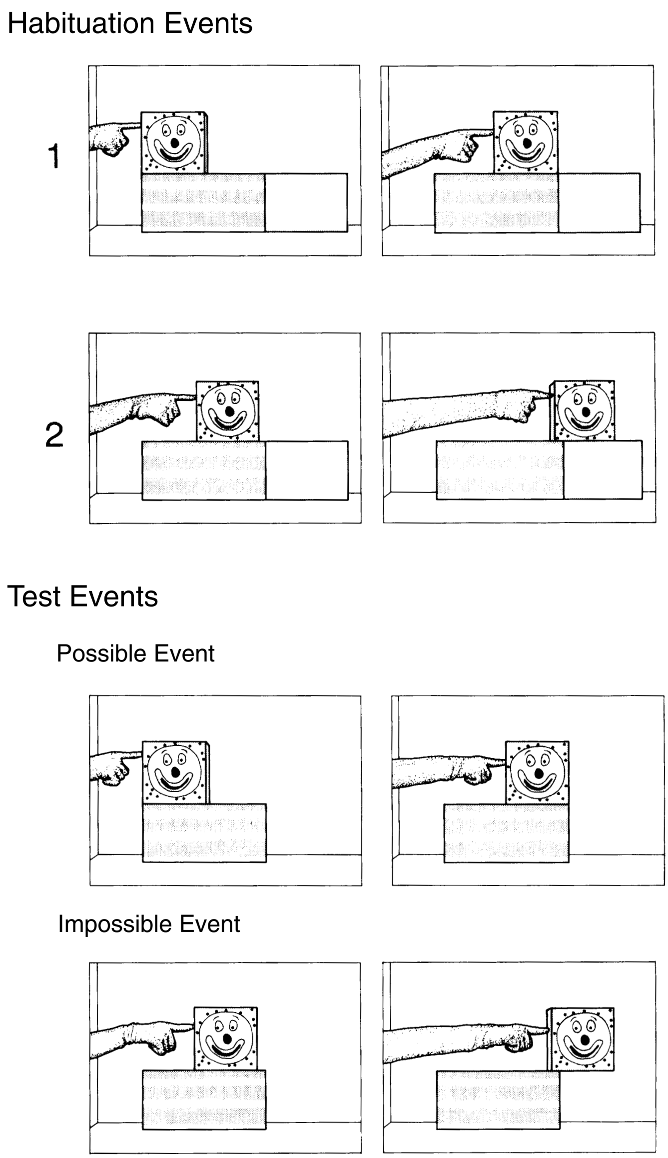


FIGURE 4.2 *Habituation and test for physical concepts. SOURCE: Test events used in Baillargeon, Needham, and Devos (1992).*

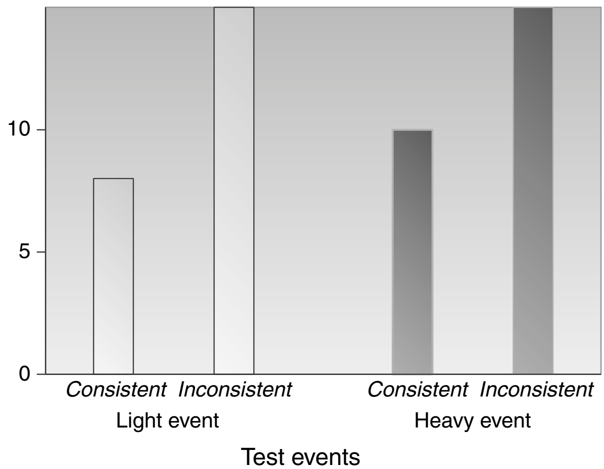


FIGURE 4.3 *Average visual fixation duration. SOURCE: Adapted from Schilling and Clifton (1998).*

need for a point of contact to bring inanimate objects into range. For example, Jacqueline (9 months) discovers that she can bring a toy within reach by pulling a blanket (support) on which it is placed. During the weeks that follow, she frequently uses this "schema" (Piaget, 1952:285). Lucienne (12 months), once having witnessed the action of the support, rapidly generalized the schema to sheets, handkerchiefs, table cloths, pillows, boxes, books, and so on. Once the baby understood the notion of the support, this knowledge transferred rapidly to a variety of potential supports. The same learning is true of stick-like things (push schema) and string-like objects (pull schema), as "means for bringing" (Piaget, 1952:295). Each new acquisition brings with it its own realm of generalization.

A series of laboratory studies has reaffirmed and extended Piaget's original naturalistic observations and provided a fairly detailed description of development of the push/pull schema from 4 to 24 months of age. As noted above, Leslie showed that 7-month-olds are sensitive to the need for point of contact in a pushing scenario. Bates et al. (1980) looked at infants' ability to reach a toy using various tools. And Brown and Slattery (described in Brown, 1990) looked at children's ability to choose the correct tool (with adequate length, rigidity, and pushing or pulling head) from an array of available tools. It was not until 24 months of age that children immediately selected the adequate tool, but by 14 months children could do so with some practice. Across the age range of 10-24 months, children first used tools effectively that were physically attached (unbreakable contact) in contrast to tools that could be unattached at the contact point (breakable contact) or when the point of contact needed to be imagined (no contact). Children showed distress or surprise at trick events—when a tool appeared to be attached but wasn't or vice versa, thus violating their pulling schema (Brown, 1990).

These studies, taken together, paint an interesting developmental scenario. Although children in habituation paradigms seem to understand the need for point of contact early (5-7 months), they cannot at 10 months apply that knowledge to tool use tasks *unless* the contact between the tool and the goal is provided in the physical layout of the task: the tool touches the object; the solution is physically situated in the environment itself. Several months later, infants can learn, with a demonstration, to envision the point of contact that is not specified in the visual array, but is invited by the pulling features of the tools. They can see that a hook would work in getting the tool if it is rigid and long enough. By 24 months, children readily note the pulling potential of unattached tools and can make a choice between available tools on the basis of their adequacy. The research shows that young children have the requisite knowledge in some sense very early on, but they need help in the form of demonstrations to prompt the application of what they know.

Biological Causality

During the past 30 years, a great deal has been learned about primitive concepts of biological causality. We concentrate here on the differences between animate and inanimate objects.

Infants learn rapidly about the differences between inanimate and animate: as we have seen, they know that inanimate objects need to be pushed or propelled into motion. Infants as young as 6 months can distinguish animate versus inanimate movements as patterns of lights attached to forces or people (Bertenthal, 1993). And Spelke (1990) has shown that if two people come close together and move away in tandem without touching, 7-months-olds show no surprise; but if two people-sized inanimate objects come together and move without a point of contact, they are perturbed (as measured by the habituation paradigm).

Young children show an early understanding that animate objects have the potential to move themselves because they are made of "biological stuff"—they obey what R. Gelman (1990) calls the "innards principle of mechanism." Inanimate objects, in contrast, obey the external-agent principle: they cannot move themselves, but must be propelled into action by an external force.

For example, Massey and Gelman (1988) reported that 3- and 4-year-old children correctly responded when asked if novel objects like an echidna and a statue can move themselves up and down a hill. Despite the fact that the echidna looked less like a familiar animal than did a statue, the children claimed that only the living object could move itself up and down a hill.

Similarly, young children in this age range can give sensible answers to questions about the difference between the insides and outsides of animals, machines, and natural inanimate objects; see Figure 4.4.

These are only a handful of findings from a large body of research that goes a long way to challenge the idea that young children are incapable of considering non-perceptual data in scientific areas. Given that there is a mounting body of evidence showing that youngsters are busy constructing coherent accounts of their physical and biological worlds, one needs to ask to what extent these early competencies serve as a bridge for further learning when they enter school.

Early Number Concepts

An ever-increasing body of evidence shows that the human mind is endowed with an implicit mental ability that facilitates attention to and use of representations of the number of items in a visual array, sequence of drumbeats, jumps of a toy bunny, numerical values represented in arrays, etc. For example, Starkey et al. (1990) showed 6- to 8-month-old infants a series of photographic slides of either 2- or 3-item displays. Each successive picture showed different household items, including combs, pipes, lemons, scissors, and corkscrews that varied in color, shape, size, and texture and spatial position. Half of the infants saw a series of two-item displays while the other half were shown a series of three-item displays. When they became bored, their looking times dropped by 50 percent (they habituated). At this point, they were then shown displays that alternated between two and three items, and if the displays showed a different number of items from what they had seen before, the infants began to show interest by looking again. The only common characteristic within the two-item and three-item displays was their numerical value, so one can say the infants habituated to the set of two or three things and then recovered interest when they were shown a different number of things. The infants could have focused on perceptual attributes of the items such as their shapes, motion, textural complexity, and so on, but they did not. This is an important clue that they are able to process information that represents number at a rather abstract level.

Other researchers have shown that infants pay attention to the number of times a toy rabbit jumps up and down, so long as the number of jumping events they have to keep track of is kept between two and four jumps (Wynn, 1996). An especially interesting demonstration of infants' ability to notice abstract number information in the environment was reported by Canfield and Smith (1996). They found that 5-month-old infants used visual expectation (see previous section) to show that infants are able to distinguish three pictures presented in one location from two pictures in another.

Young infants and toddlers also respond correctly to the effects of the

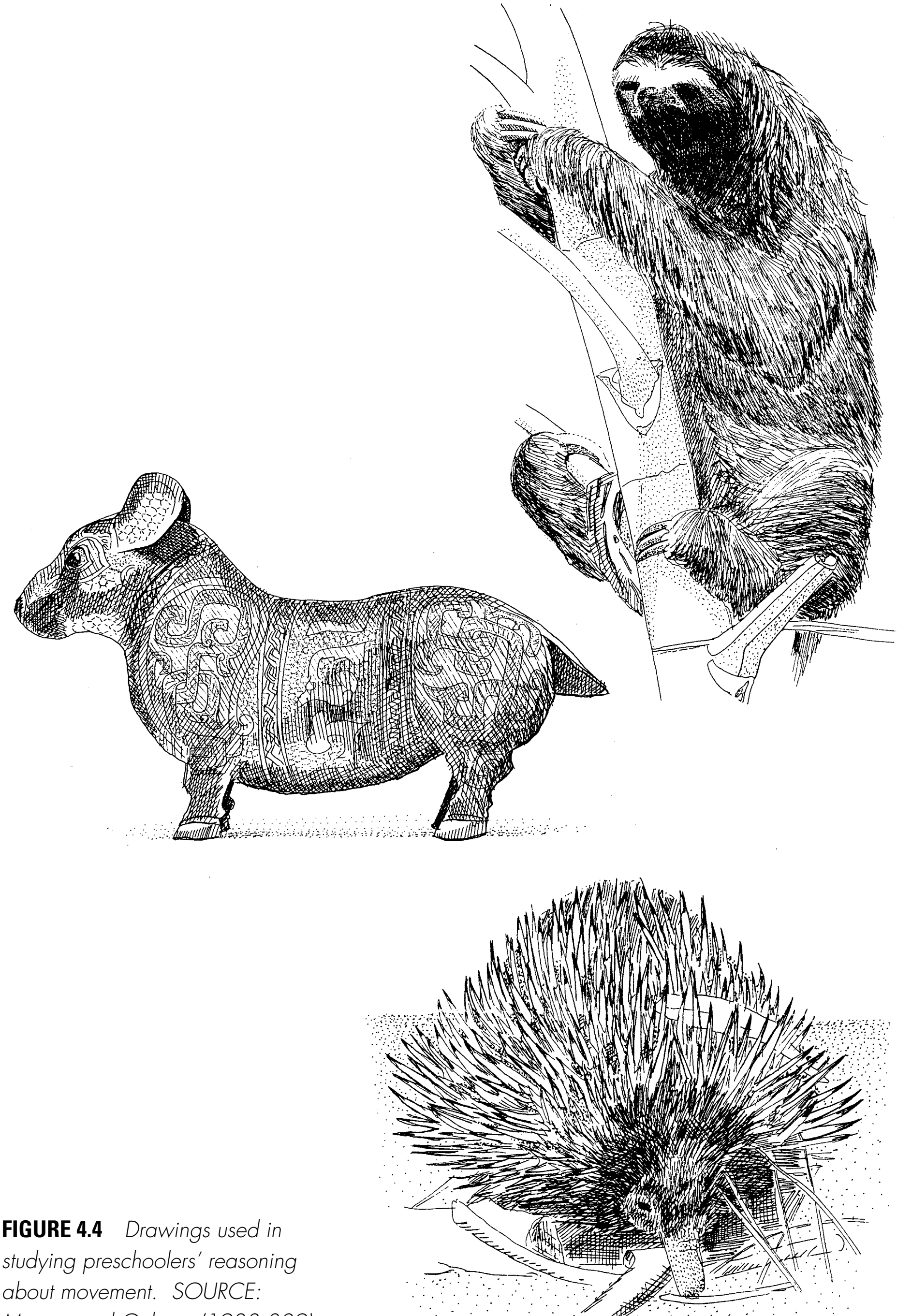


FIGURE 4.4 *Drawings used in studying preschoolers' reasoning about movement. SOURCE: Massey and Gelman (1988:309).*

arithmetic operations of adding and subtracting. Through their surprise or search reactions, young children are able to tell us when an item is added or subtracted from what they expected (Wynn, 1990, 1992a, b; Starkey, 1992). For example, 5-month-old infants first saw two objects repeatedly; then a screen covered the objects and they watched as an experimenter proceeded to add another object or remove one from the hidden display. The screen was then removed, revealing one more or one less item than before. In both the less and more conditions, infants looked longer at the numerically "incorrect" display—that is, the unexpected value that did not correspond to their initial training; if they saw one added, they expected three, not one, and vice versa (Wynn, 1992a, b).

Experimental evidence of this kind implies a psychological process that relates the effect of adding or removing items to a *numerical representation* of the initial display. A similar line of evidence with preschool children indicates that very young children are actively engaged in using their implicit knowledge of number to attend to and make sense of novel examples of numerical data in their environments; see Box 4.2.

There are many other demonstrations of young children's interpreting sets of objects in terms of number. Together, the findings indicate that even young children can actively participate in their own learning and problem solving about number. This ability is why children often deal with novel conditions rather well, as when they tell puppets who are "just learning to count" if they are correct and if they are wrong or even invent counting solutions (Groen and Resnick, 1977; Siegler and Robinson, 1982; Starkey and Gelman, 1982; Sophian, 1994).

But just because children have some knowledge of numbers before they enter school is not to say that there is little need for careful learning later. Early understanding of numbers can guide their entry into school-based learning about number concepts. Successful programs based on developmental psychology already exist, notably the Right Start Program (Griffin and Case, 1997). Although making the entry levels easier, these early number concepts can also be problematic when it comes to the transitions to higher-level mathematics. Rational numbers (fractions) do not behave like whole numbers, and attempting to treat them as such leads to serious problems. It is therefore noteworthy that many children experience just these sorts of problems in mathematics when they encounter "fractions": They believe the larger number always represents a bigger quantity or larger unit.

Early Attention to Language

We introduced the idea that children come equipped with the means necessary for understanding their worlds when considering physical and biological concepts. It should not be surprising that infants also possess

BOX 4.2 How Many?

How do 3- to 5-year old children react when they encounter unexpected changes in the number of items? Before the dialog below, children had been playing with five toy mice that were on a plate; the plate and mice were then covered and the experimenter surreptitiously took away two mice before uncovering the plate (Gelman and Gallistel, 1978:172). What follows is one child's attempts to reconcile the differences in the number of mice:

Child:	*Must have disappeared.*
Experimenter:	*What?*
Child:	*The other mousses?...*
Experimenter:	*How many now?*
Child:	*One, two, three.*
Experimenter:	*How many at the beginning of the game?*
Child:	*There was one there, one there, one there, one there, one there.*
Experimenter:	*How many?*
Child:	*Five—this one is three now but before it was five.*
Experimenter:	*What would you need to fix the game?*
Child:	*I'm not really sure because my brother is real big and he could tell.*
Experimenter:	*What do you think he would need?*
Child:	*Well I don't know...Some things have to come back.*
Experimenter:	[Hands the child some objects including four mice].
Child:	[Puts all four mice on the plate]. *There. Now there's one, two, three, four, five, six, seven! No...I'll take these* [points to two] *off and we'll see how many.*
Child:	[Removes one and counts]. *One, two, three, four, five; no—one, two, three, four. Uh...there were five, right?*
Experimenter:	*Right.*
Child:	*I'll take out this one here [on the table] and then we'll see how many there is now.*
Child:	[Takes one off and counts]. *One, two, three, four, five. Five! Five.*

such mechanisms for learning language. They begin at an early age to develop knowledge of their linguistic environments, using a set of specific mechanisms that guide language development.

Infants have to be able to distinguish linguistic information from nonlinguistic stimuli: they attribute meaning and linguistic function to words and not to dog barks or telephone rings (Mehler and Christophe, 1995). By 4 months of age, infants clearly show a preference for listening to words over other sounds (Colombo and Bundy, 1983). And they can distinguish changes in language. For example, after being habituated to English sentences, infants detected the shift to a different language, such as Spanish; they did not register shifts to different English utterances (Bahrick and Pickens, 1988), which indicates that they noticed the novel Spanish utterances. Figure 4.5 illustrates that American-born infants, at 2 months of age, start reacting to English utterances significantly faster than they do to French utterances. Young infants learn to pay attention to the features of speech, such as intonation and rhythm, that help them obtain critical information about language and meaning. As they get older, they concentrate on utterances that share a structure that corresponds to their maternal language, and they neglect utterances that do not.

By 6 months of age, infants distinguish some of the properties that characterize the language of their immediate environment (Kuhl et al., 1992). Around 8-10 months of age, infants stop treating speech as consisting of mere sounds and begin to represent only the linguistically *relevant* contrasts (Mehler and Christophe, 1995). For example, Kuhl et al. (1992) have shown that the contrasts “ra” and “la” can be learned by very young English and Japanese babies alike, but later on only the contrast relevant to the mother

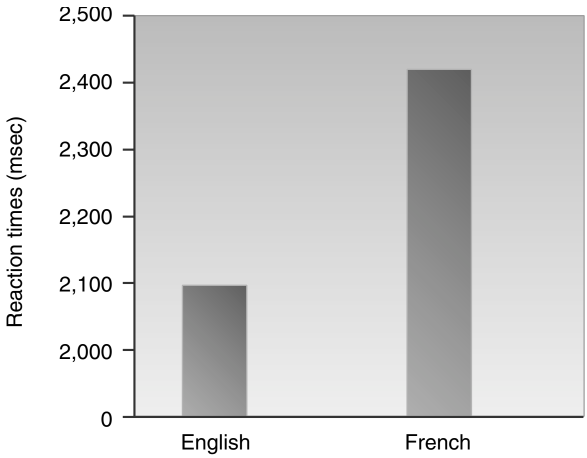


FIGURE 4.5 *Reaction time to French and English sentences for 2-month-old infants. Mean latencies of initiation of a visual saccade in the direction of the sound for American 2-month-olds listening to French and English sentences. SOURCE: Adapted from Mehler and Christophe (1995:947).*

language is retained as the other one drops out (e.g., "la" drops out for Japanese infants). Such studies illustrate that the learning environment is critical for determining what is learned even when the basic learning mechanisms do not vary.

Young infants are also predisposed to attend to the language spoken by others around them. They are attracted to human faces, and look especially often at the lips of the person speaking. They appear to expect certain types of coordination between mouth movements and speech. When shown videos of people talking, infants can detect the differences between lip movements that are synchronized with the sounds and those that are not.

Young children also actively attempt to understand the meaning of the language that is spoken around them. Roger Brown (1958) discussed "The Original Word Game" that children play with parents. Successful participation involves the child's making inferences about what someone must mean by paying attention to the surrounding context. Parents of 1-year-olds report that their children understand much of what is said to them, although there is obviously a great deal of information that children really do not understand (Chapman, 1978). For example, Lewis and Freedle (1973) analyzed the comprehension abilities of a 13-month-old child. When handed an apple while she was in her high chair and told "Eat the apple," the child bit it. When handed an apple while playing in her playpen and told "Throw the apple," the child threw it. Lewis and Freedle performed an experiment in order to test whether the child really understood words such as "eat" and "throw." They handed the child an apple while she was in her high chair and asked her to "throw the apple." The child bit it. Later, when the child was in her playpen she was handed an apple and told "eat the apple." She threw it. The child's strategy was basically to assume that she should "do what you usually do in this situation." This sound strategy is frequently correct.

In everyday settings, young children have rich opportunities for learning because they can use context to figure out what someone must mean by various sentence structures and words. Unless she was being tested by tricky experimenters, for example, the child discussed above could determine the general meanings of "apple," "eat," and "throw." Similarly, if a mother says "Get your shirt" while pointing to the only loose object (a shirt) on the rug, the child begins to understand the meaning of "get" and "shirt." Language acquisition cannot take place in the absence of shared social and situational contexts because the latter provide information about the meanings of words and sentence structures (Chapman, 1978). The child uses meaning as a clue to language rather than language as a clue to meaning (MacNamara, 1972). Parents and other caregivers take into account both context and children's emerging abilities as they help them extend their competencies. The extremely important guiding role that caregivers have in children's cognitive development is discussed further below.

Language development studies illustrate that children's biological capacities are set into motion by their environments. The biological underpinnings enable children to become fluent in language by about age three, but if they are not in a language-using environment, they will not develop this capacity. Experience is important; but the opportunity to use the skills—practice—is also important. Janellen Huttenlocher, for example, has shown that language has to be practiced as an ongoing and active process and not merely passively observed by watching television (Huttenlocher, cited in *Newsweek*, 1996).

STRATEGIES FOR LEARNING AND METACOGNITION

So far we have reviewed research that has tapped into infants' amazing competencies that biologically predispose them to learn. These predispositions help prepare human infants for the complex challenges of adaptive learning that come later in life. In order to thrive, children must still engage in self-directed and other-directed learning, even in areas of early competence. In this section we look at how children learn about things that they would not be predisposed to attend to, such as chess or the capital cities of countries. We discuss how children come to be able to learn almost anything through effort and will.

It has generally been assumed that in the arena of deliberate, intentional, mindful, and strategic learning, young children are woefully inadequate. But recent scientific studies have revealed hitherto unsuspected strategic competence and metacognitive knowledge in young children.

The Importance of Capacity, Strategies, Knowledge, and Metacognition

A traditional view of learning and development was that young children know and can do little, but with age (maturation) and experience (of any kind) they become increasingly competent. From this view, learning is development and development is learning. There is no need to postulate special forms of learning nor for learners to be particularly active (see Bijou and Baer, 1961; Skinner, 1950). Yet even in privileged domains, as described above, this passive view does not fully apply.

In addition, research in another major area began to show how learners process information, remember, and solve problems in nonprivileged domains. Known as information processing (Simon, 1972; Newell and Simon, 1972), this branch of psychology was quickly adopted to explain developments in children's learning. All human learners have limitations to their short-term memory for remembering and for solving problems. Simon (1972) and others (e.g., Chi, 1978; Siegler, 1978; Klahr and Wallace, 1973) argued that development means overcoming information-processing constraints, such as limited short-term memory capacity. The crucial argument for developmental psychologists is whether young learners are particularly hampered by memory limitations and whether, compared with adults, they are less able to overcome general limitations through the clever use of strategies or by lack of relevant knowledge factors.

One view of learning in children is that they have a less memory capacity than adults. While there is no doubt that, in general, children's learning and memory abilities increase with age, controversy surrounds the mechanisms that affect these changes. One view is that children's short-term memory capacity, or the amount of mental space they have (M-space), increases as children mature (Pascual-Leone, 1988). With more mental space, they can retain more information and perform more complex mental operations. A complementary view is that the mental operations of older children are more rapid, enabling them to make use of their limited capacity more effectively (Case, 1992). If one holds either of these positions, one would expect relatively uniform improvement in performance across domains of learning (Case, 1992; Piaget, 1970).

A second view is that children and adults have roughly the same mental capacity, but that with development children acquire knowledge and develop effective activities to use their minds well. Such activities are often called strategies. There are a variety of well-known strategies that increase remembering, such as rehearsal (repeating items over and over), which tends to improve rote recall (Belmont and Butterfield, 1971); elaboration (Reder and Anderson, 1980), which improves retention of more meaningful units such as sentences; and summarization (Brown and Day, 1984), which increases retention and comprehension. These are just three of many strategies.

Perhaps the most pervasive strategy used to improve memory performance is clustering: organizing disparate pieces of information into meaningful units. Clustering is a strategy that depends on organizing knowledge. In a classic paper, Miller (1956) described the persistence of a phenomenon he called the "magical number 7 ± 2" in human mental processing. Given a list of numbers to remember, sounds (phonemes) to distinguish from one another, or a set of unrelated facts to recall, there is a critical change in performance at around seven items. Up to seven items (between five and nine, actually, hence Miller's title), people can readily handle a variety of tasks; with more than seven, they simply cannot process them handily. People have developed ways around this memory constraint by organizing information, such as grouping together or "chunking" disparate elements into sets of letters, numbers, or pictures that make sense to them.

Known as the chunking effect, this memory strategy improves the performance of children, as well as adults. A prototype experiment would involve, for example, presenting 4- to 10-year-olds with long lists of pictures to remember, far more than they could if they simply tried to remember them individually. Such a list might consist of pictures of a cat, rose, train, hat, airplane, horse, tulip, boat, coat, etc. Given a 20-item list, older children remember more than younger children, but the factor responsible for better recall is not age per se, but whether the child notices that the list consists of four *categories* (animals, plants, means of transportation, and articles of clothing). If the categories are noticed, young children often recall the entire list. In the absence of category recognition, performance is poorer and shows the age effect. Younger children employ categorization strategies less often than older ones. However, the skill is knowledge related, not age related; the more complex the categories, the older the child is before noticing the structure. One has to know a structure before one can use it.

These varying views of children's learning have different implications for what one expects from children. If one believes that learning differences are determined by gradual increases in capacity or speed of processing, one would expect relatively uniform increases in learning across most domains. But if one believes that strategies and knowledge are important, one would expect different levels of learning, depending on the children's conceptual knowledge and their control over strategies that organize that knowledge for learning. For example, in a comparison of college students' and third graders' abilities to recall 30 items that included the names of Saturday morning television shows, children's cartoon characters, etc., the third graders clustered more and subsequently recalled more (Linberg, 1980). Similarly, a group of 8- to 12-year-old "slow learners" performed much better than "normal" adults on a task of recalling large numbers of pop stars because of a clustering strategy (Brown and Lawton, 1977). An outstanding example of the intertwining of capacity, knowledge, and strategies in children's chess performance is provided in Box 2.1 (see Chapter 2).

Metacognition is another important aspect of children's learning (see Brown, 1978; Flavell and Wellman, 1977). The importance of prior knowledge in determining performance, crucial to adults as well as children, includes knowledge about learning, knowledge of their own learning strengths and weaknesses, and the demands of the learning task at hand. Metacognition also includes self-regulation—the ability to orchestrate one's learning: to plan, monitor success, and correct errors when appropriate—all necessary for effective intentional learning (Bereiter and Scardamalia, 1989).

Metacognition also refers to the ability to reflect on one's own performance. Whereas self-regulation may appear quite early, reflection appears to be late developing. If children lack insight to their own learning abilities, they can hardly be expected to plan or self-regulate efficiently. But metacognition does not emerge full-blown in late childhood in some "now you have it, now you don't" manner. The evidence suggests that, like other forms of learning, metacognition develops gradually and is as dependent on knowledge as experience. It is difficult to engage in self-regulation and reflection in areas that one does not understand. However, on topics that children know, primitive forms of self-regulation and reflection appear early (Brown and DeLoache, 1978).

Attempts at deliberate remembering in preschool children provide glimpses of the early emergence of the ability to plan, orchestrate, and apply strategies. In a famous example, 3- and 4-year-old children were asked to watch while a small toy dog was hidden under one of three cups. The children were instructed to remember where the dog was. The children were anything but passive as they waited alone during a delay interval (Wellman et al., 1975). Some children displayed various behaviors that resemble well-known mnemonic strategies, including clear attempts at retrieval practice, such as looking at the target cup and nodding yes, looking at the non-target cups and nodding no, and retrieval cueing, such as marking the correct cup by resting a hand on it or moving it to a salient position. Both of these strategies are precursors to more mature rehearsal activities. These efforts were rewarded: children who prepared actively for retrieval in these ways more often remembered the location of the hidden dog. Box 4.3 shows a glimmer of even earlier emergence of "rehearsal."

These attempts to aid remembering involve a dawning awareness of metacognition—that without some effort, forgetting would occur. And the strategies involved resemble the more mature forms of strategic intervention, such as rehearsal, used by older school-aged children. Between 5 and 10 years of age, children's understanding of the need to use strategic effort in order to learn becomes increasingly sophisticated, and their ability to talk about and reflect on learning continues to grow throughout the school years (Brown et al., 1983). By recognizing this dawning understanding in children, one can begin to design learning activities in the early school years that build on and strengthen their understanding of what it means to learn and remember.

Multiple Strategies, Strategy Choices

The strategies that children use to memorize, conceptualize, reason, and solve problems grow increasingly effective and flexible, and are applied more broadly, with age and experience. But different strategies are not solely related to age. To demonstrate the variety, we consider the specific case of the addition of single-digit numbers, which has been the subject of a great deal of cognitive research.

Given a problem such as 3 + 5, it was initially believed that preschool children add up from 1 (i.e., 1,2,3|4,5,6,7,8), that 6- to 8-year-olds add by

BOX 4.3 Remembering Where Big Bird Is

For a group of 18- and 24-month-old children, an attractive toy, Big Bird, was hidden in a variety of locations in a playroom, such as behind a pillow, on a couch, or under a chair. The children were told that "Big Bird is going to hide, and when the bell rings, you can find him." While waiting to retrieve the toy, even though they were engaged by an adult in play and conversation, the children did not wait passively. Instead, they often interrupted their play with a variety of activities that showed they were still preoccupied with the memory task. They talked about the toy, saying, "Big Bird"; the fact that it was hidden, "Big Bird hiding"; where it was hidden, "Big Bird, chair"; or about their plan to retrieve it later, "Me find Big Bird." Other rehearsal-like behaviors included looking or pointing at the hiding place, hovering near it, and attempting to peek at the toy. Although less systematic and well formed than an older person's rehearsal strategies, the young children's activities similarly function to keep alive the information to be remembered, the hidden toy and its location (DeLoache et al., 1985a).

counting from the larger number ("5, then 6, 7, 8,"), and that from 9 years on, children retrieve answers from memory because they know the answer (Ashcraft, 1985; Resnick and Ford, 1981). More recently, however, a more complex and interesting picture has emerged (Siegler, 1996). On a problem-by-problem basis, children of the same age often use a wide variety of strategies. This finding has emerged in domains as diverse as arithmetic (Cooney et al., 1988; Geary and Burlingham-Dubree, 1989; Goldman et al., 1988; Siegler and Robinson, 1982), causal and scientific reasoning (Lehrer and Schauble, 1996; Kuhn, 1995; Schauble, 1990; Shultz, 1982), spatial reasoning (Ohlsson, 1991); referential communications (Kahan and Richards, 1986), recall from memory (Coyle and Bjorklund, 1997), reading and spelling (Jorm and Share, 1983), and judgments of plausibility (Kuhara-Kojima and Hatano, 1989). Even the same child presented the same problem on two successive days often uses different strategies (Siegler and McGilly, 1989). For example, when 5-year-olds add numbers, they sometimes count from 1, as noted above, but they also sometimes retrieve answers from memory, and sometimes they count from the larger number (Siegler, 1988).

The fact that children use diverse strategies is not a mere idiosyncrasy of human cognition. Good reasons exist for people to know and use multiple strategies. Strategies differ in their accuracy, in the amounts of time their execution requires, in their processing demands, and in the range of problems to which they apply. Strategy choices involve tradeoffs among these properties. The broader the range of strategies that children know and can appreciate where they apply, the more precisely they can shape their approaches to the demands of particular circumstances.

Even young children can capitalize on the strengths of different strategies and use each one for the problems for which its advantages are greatest. For example, for an easy addition problem such as 4+1, first graders are likely to retrieve the answer; for problems with large differences between the numbers, such as 2+9, they are likely to count from the larger number ("9,10,11"); for problems excluding both of these cases, such as 6+7, they are likely to count from one (Geary, 1994; Siegler, 1988). The adaptiveness of these strategy choices increases as children gain experience with the domain, though it is obvious even in early years (Lemaire and Siegler, 1995).

Once it is recognized that children know multiple strategies and choose among them, the question arises: How do they construct such strategies in the first place? This question is answered through studies in which individual children who do not yet know a strategy are given prolonged experiences (weeks or months) in the subject matter; in this way, researchers can study how children devise their various strategies (Kuhn, 1995; Siegler and Crowley, 1991; see also DeLoache et al., 1985a). These are referred to as "microgenetic" studies, meaning small-scale studies of the development of a concept. In this approach, one can identify when a new strategy is first used, which in turn allows examination of what the experience of discovery was like, what led to the discovery, and how the discovery was generalized beyond its initial use.

Three key findings have emerged from these studies: (1) discoveries are often made not in response to impasses or failures but rather in the context of successful performance; (2) short-lived transition strategies often precede more enduring approaches; and (3) generalization of new approaches often occurs very slowly, even when children can provide compelling rationales for their usefulness (Karmiloff-Smith, 1992; Kuhn, 1995; Siegler and Crowley, 1991). Children often generate useful new strategies without ever having generated conceptually flawed ones. They seem to seek conceptual understanding of the requisites of appropriate strategies in a domain. On such tasks as single-digit addition, multidigit subtraction, and the game of tic-tac-toe, children possess such understanding, which allows them to recognize the usefulness of new, more advanced strategies before they generate them spontaneously (Hatano and Inagaki, 1996; Siegler and Crowley, 1994).

The new understanding of children's strategic development has led to instructional initiatives. A common feature of such innovations as reciprocal teaching (Palincsar and Brown, 1984), communities of learners (Brown and Campione, 1994, 1996; Cognition and Technology Group at Vanderbilt, 1994), the ideal student (Pressley et al., 1992), and Project Rightstart (Griffin et al., 1992) is that they recognize the importance of students' knowing and using diverse strategies. These programs differ, but all are aimed at helping students to understand how strategies can help them solve problems, to recognize when each strategy is likely to be most useful, and to transfer strategies to novel situations. The considerable success that these instructional programs have enjoyed, with young as well as older children and with low-income as well as middle-income children, attests to the fact that the development of a repertoire of flexible strategies has practical significance for learning.

Multiple Intelligences

Just as the concept of multiple strategies has improved understanding of children's learning and influenced approaches to education, so, too, has the growing interest in multiple forms of intelligence. In his theory of multiple intelligences, Gardner (1983, 1991) proposed the existence of seven relatively autonomous intelligences: linguistic, logical, musical, spatial, bodily kinesthetic, interpersonal, and intrapersonal. Recently, Gardner (1997) proposed an eighth intelligence, "naturalistic." The first two intelligences are those typically tapped on tests and most valued in schools.

The theory of multiple intelligences was developed as a psychological theory, but it sparked a great deal of interest among educators, in this country and abroad, in its implications for teaching and learning. The experimental educational programs based on the theory have focused generally in two ways. Some educators believe that all children should have each intelligence nurtured; on this basis, they have devised curricula that address each intelligence directly. Others educators have focused on the development of specific intelligences, like the personal ones, because they believe these intelligences receive short shrift in American education. There are strengths and weaknesses to each approach.

The application of multiple intelligences to education is a grass roots movement among teachers that is only just beginning. An interesting development is the attempt to modify traditional curricula: whether one is teaching history, science, or the arts, the theory of multiple intelligences offers a teacher a number of different approaches to the topic, several modes of representing key concepts, and a variety of ways in which students can demonstrate their understandings (Gardner, 1997).

CHILDREN'S VIEWS OF INTELLIGENCE AND THEIR LEARNING: MOTIVATION TO LEARN AND UNDERSTAND

Children, like their elders, have their own conceptions about their minds and those of others and how humans learn and are "intelligent" (see Wellman, 1990; Wellman and Hickey, 1994; Gelman, 1988; Gopnik, 1990). Children are said to have one of two main classes of beliefs: entity theories and incremental theories (Dweck, 1989; Dweck and Elliot, 1983; Dweck and Leggett, 1988). Children with entity theories believe that intelligence is a fixed property of individuals; children with incremental theories believe that intelligence is malleable (see also Resnick and Nelson-LeGall, 1998). Children who are entity theorists tend to hold performance goals in learning situations: they strive to perform well or appear to perform well, attain positive judgments of their competence, and avoid assessments. They avoid challenges that will reflect them in poor light. They show little persistence in the face of failure. Their aim is to perform well. In contrast, children who are incremental theorists have learning goals: they believe that intelligence can be improved by effort and will. They regard their own increasing competence as their goal. They seek challenges and show high persistence. It is clear that children's theories about learning affect how they learn and how they think about learning. Although most children probably fall on the continuum between the two theories and may simultaneously be incremental theorists in mathematics and entity theorists in art, the motivational factors affect their persistence, learning goals, sense of failure, and striving for success. Teachers can guide children to a more healthy conceptualization of their learning potential if they understand the beliefs that children bring to school.

Self-Directed and Other-Directed Learning

Just as children are often self-directed learners in privileged domains, such as those of language and physical causality, young children exhibit a strong desire to apply themselves in intentional learning situations. They also learn in situations where there is no external pressure to improve and no feedback or reward other than pure satisfaction—sometimes called achievement or competence motivation (White, 1959; Yarrow and Messer, 1983; Dichter-Blancher et al., 1997). Children are both problem solvers and problem generators; they not only attempt to solve problems presented to them, but they also seek and create novel challenges. An adult struggling to solve a crossword puzzle has much in common with a young child trying to assemble a jigsaw puzzle. Why do they bother? It seems that humans have a need to solve problems; see Box 4.4. One of the challenges of schools is to build on children's motivation to explore, succeed, understand (Piaget, 1978) and harness it in the service of learning.

GUIDING CHILDREN'S LEARNING

Along with children's natural curiosity and their persistence as self-motivated learners, what they learn during their first 4 or 5 years is not learned

BOX 4.4 Solving a Problem

Children 18 to 36 months of age are given nesting cups to play with (DeLoache et al., 1985b; see also Karmiloff-Smith and Inhelder, 1974, on children balancing blocks). Five plastic cups are dumped on a table in front of a child, who is simply told, "These are for you to play with." Although the children have previously seen the cups nested together, there was no real need for them to attempt to nest the cups themselves; they could easily have stacked them, made an imaginary train, pretended to drink from them, etc. However, the children immediately started trying to fit the cups together, often working long and hard in the process.

Overall, in their spontaneous manipulations of a set of nesting cups, very young children progress from trying to correct their errors by exerting physical force without changing any of the relations among the elements, to making limited changes in a part of the problem set, to considering and operating on the problem as a whole. This "developmental" trend is observed not only across age, but also in the same children of the same age (30 months) given extensive time to play with the cups.

Most important, the children persist, not because they have to, or are guided to, or even because they are responding to failure; they persist because success and understanding are motivating in their own right.

in isolation. Infants' activities are complemented by adult-child relationships that encourage the gradual involvement of children in the skilled and valued activities of the society in which they live. Research has shown that learning is strongly influenced by these social interactions. In fact, studies of interactions of drug-abusing mothers and their infants show how the absence of these critical learning interactions depresses 3- and 6-month-old infants' learning (Mayes et al., 1998).

Parents and others who care for children arrange their activities and facilitate learning by regulating the difficulty of the tasks and by modeling mature performance during joint participation in activities. A substantial body of observational research has provided detailed accounts of the learning interactions between mothers and their young children. As an illustration, watch a mother with a 1-year-old sitting on her knees in front of a collection of toys. A large part of her time is devoted to such quietly facilitative and scene-setting activities as holding a toy that seems to require three hands to manipulate, retrieving things that have been pushed out of range, clearing away those things that are not at present being used in order to provide the child with a sharper focus for the main activity, turning toys so that they become more easily grasped, demonstrating their less obvious properties, and all along molding her body in such a way as to provide maximal physical support and access to the play materials (Schaffer, 1977:73).

In addition to the research showing how adults arrange the environment to promote children's learning, a great deal of research has also been conducted on how adults guide children's understanding of how to act in new situations through their emotional cues regarding the nature of the situation, nonverbal models of how to behave, verbal and nonverbal interpretations of events, and verbal labels to classify objects and events (Rogoff, 1990; Walden and Ogan, 1988). Parents frame their language and behavior in ways that facilitate learning by young children (Bruner, 1981a, b, 1983; Edwards, 1987; Hoff-Ginsberg and Shatz, 1982). For example, in the earliest months, the restrictions of parental baby talk to a small number of melodic contours may enable infants to abstract vocal prototypes (Papousek et al., 1985). Parental labeling of objects and categories may assist children in understanding category hierarchies and learning appropriate labels (Callanan, 1985; Mervis, 1984). Communication with caregivers to accomplish everyday goals is the groundwork for children's early learning of the language and other cognitive tools of their community; see Box 4.5.

An extremely important role of caregivers involves efforts to help children connect new situations to more familiar ones. In our discussion of competent performance and transfer (see Chapter 3), we noted that knowledge appropriate to a particular situation is not necessarily accessed despite being relevant. Effective teachers help people of all ages make connections among different aspects of their knowledge.

Caregivers attempt to build on what children know and extend their competencies by providing supporting structures or scaffolds for the child's performance (Wood et al., 1976). Scaffolding involves several activities and tasks, such as:

- interesting the child in the task;
- reducing the number of steps required to solve a problem by simplifying the task, so that a child can manage components of the process and recognize when a fit with task requirements is achieved;
- maintaining the pursuit of the goal, through motivation of the child and direction of the activity;
- marking critical features of discrepancies between what a child has produced and the ideal solution;
- controlling frustration and risk in problem solving; and
- demonstrating an idealized version of the act to be performed.

Scaffolding can be characterized as acting on a motto of "Where before there was a spectator, let there now be a participant" (Bruner, 1983:60).

BOX 4.5 Which Toy?

Consider the efforts to reach an understanding between an adult and a 14-month-old about which toy the infant wants to play with. The adult is looking for a toy in the toy box. When he touches the tower of rings, the baby exclaims, "Aa!" The adult responds, "Aa?" picking up the tower. The infant continues looking at the toy box and ignores the tower, so the adult shows the baby the tower and again asks "Aa?" The baby points at something in the toy box grunting, "Aa . . . aa . . . " The adult reaches toward the toy box again, and the infant exclaims, "Tue!" The adult exclaimed "Aa!" as he picks up the peekaboo cloth and shows it to the infant. But the infant ignores the cloth and points again at something in the toy box, then, impatiently, waves his arm. The adult responds, "Aa?" But the baby points down to the side of the toy box. They repeat the cycle with another toy, and the baby waves his arm impatiently. The adult says "You show me!" and lifts the baby to his lap from the high chair. The adult then picks up the jack-in-the-box, asking, "This?"—the baby opens his hand toward the toy, and they began to play (Rogoff et al., 1984:42-43).

Learning to Read and Tell Stories

The importance of adult support of children's learning can be demonstrated by considering the question: How is it that children, born with no language, can develop most of the rudiments of story telling in the first three years of life? (Engle, 1995). A variety of literacy experiences prepare children for this prowess. Providing children with practice at telling or "reading" stories is an impetus to the growth of language skills and is related to early independent reading; see Box 4.6. For many years some parents and scholars have known about the importance of early reading, through picture book "reading" that is connected to personal experiences. Recently, the efficacy of this process has been scientifically validated—it has been shown to work (see National Research Council, 1998).

In the late nineteenth century, C. L. Dodgson—Lewis Carroll—prepared a nursery version of his famous *Alice in Wonderland/Through the Looking Glass* books. The majority of the book consisted of reprints of the famous Tenniel woodcut illustrations. The book was to stimulate "reading" in the sense that contemporary children's wordless picture books do. This was a first of its kind, and we quote Lewis Carroll (cited in Cohen, 1995:440).

> I have reason to believe that "Alice's Adventures in Wonderland" has been read by some hundreds of English Children, aged from Five to Fifteen: also by Children aged from Fifteen to Twenty-five: yet again by Children aged

BOX 4.6 Baby Reading

Sixteenth-month-old Julie is left alone temporarily with a visiting grandfather. Wishing to distract the child from her mother's absence, he starts "reading" a picture book to her. On each page is an animal and its "baby." Julie shows interest as a spectator until they came to a picture of a kangaroo and its "joey." She quickly says "Kanga, baby." Pointing to a shirt with Kanga and Roo (from *Winnie the Pooh*), she says again, "Kanga" "baby." Grandfather repeats each utterance. Then he says: "Where's Julie's Kanga?" knowing that she has recently received a large stuffed animal from Australia. With great excitement, Julie pulls the stuffed animal over to her grandfather and, pointing to the book, says "Kanga, baby," then points to the stuffed toy, "Kanga" and to the joey in the pouch, "baby." Communication had been reached with much laughter and repetition of the Kanga/baby routine. Even at the one-word utterance stage, children can "read," "refer," and "represent" across settings (Brown, personal communication).

> from Twenty-five to Thirty-five . . . And my ambition now (is it a vain one?) is that it will be read by Children aged from Nought to Five. To be read? Nay, not so! Say rather to be thumbed, to be cooed over, to be dogs'-eared, to be rumpled, to be kissed, by the illiterate, ungrammatical.

A preeminent educator, Dodgson had a pedagogical creed about how "Nursery Alice" should be approached. The subtext of the book is aimed at adults, almost in the fashion of a contemporary teacher's guide; they were asked to bring the book to life. The pictures were the primary focus; much of the original tale is left unspecified. For example, when looking at the famous Tenniel picture of Alice swimming with mouse in a pool of her own tears, Carroll tells the adult to read to the child as follows (cited in Cohen, 1995:441):

> Now look at the picture, and you'll soon guess what happened next. It looks just like the sea, doesn't it? But it really is the Pool of Tears—all made of Alice's tears, you know!
>
> And Alice has tumbled into the Pool: and the Mouse has tumbled in: and there they are swimming about together.
>
> Doesn't Alice look pretty, as she swims across the picture? You can just see her blue stockings, far away under the water.
>
> But Why is the Mouse swimming away from Alice is such a hurry? Well, the reason is, that Alice began talking about cats and dogs: and a Mouse always hates talking about cats and dogs!
>
> Suppose you were swimming about, in a Pool of your own Tears: and suppose somebody began talking to you about lesson-books and bottles of medicine, wouldn't you swim as hard as you could go?

Carroll, a natural teacher, guides caretakers through the task of concentrating the child's attention on the picture, prodding the child's curiosity by asking questions, and engaging the child in a dialogue—even if the child's contribution is initially limited. Carroll asks the adult to lead the child through literacy events by developing "habits of close observation." He cleverly suggests certain truths about human and animal nature, and he opens up a realm of fun and nonsense that the child can share with the adult reading the story (Cohen, 1995:442).

When caregivers engage in picture book "reading," they can structure children's developing narrative skills by asking questions to organize children's stories or accounts (Eisenberg, 1985; McNamee, 1980). If the child stops short or leaves out crucial information, adults may prompt, "What happened next?" or "Who else was there?" Such questions implicitly provide children with cues to the desired structure of narratives in their environment.

For example, one mother began reading with her child, Richard, when he was only 8 months old (Ninio and Bruner, 1978). The mother initially did all the "reading," but at the same time she was engaged in "teaching" Richard the ritual dialogue for picture book reading. At first she appeared to be content with any vocalization from the baby, but as soon as he produced actual words, she increased her demands and asked for a label with the query, "What's that?" The mother seemed to increase her level of expectation, first coaxing the child to substitute a vocalization for a nonvocal sign and later a well-formed word for a babbled vocalization. Initially, the mother did all the labeling because she assumed that the child could not; later, the mother labeled only when she believed that the child would not or could not label for himself. Responsibility for labeling was thereby transferred from the mother to the child in response to his increasing store of knowledge, finely monitored by the mother. During the course of the study the mother constantly updated her inventory of the words the child had previously understood and repeatedly attempted to make contact with his growing knowledge base.

Middle-class children between 1-1/2 and 3 years often provide labels spontaneously. One group of children did such labeling as "There's a horsie" or asked the mothers for information "What's this?" (DeLoache, 1984). With the 3-year-olds, the mothers went far beyond labeling; they talked about the relation among the objects in the picture, related them to the children's experiences, and questioned the children about their outside experience. For example, "That's right, that's a beehive. Do you know what bees make? They make honey. They get nectar from flowers and use it to make honey, and then they put the honey in the beehive." The mothers use the situation and the material to provide the children with a great deal of background information. They continually elaborate and question information, which are comprehension-fostering activities that must later be applied to "real" reading tasks.

In these reading activities, mothers are attempting to function in what psychologists call a child's zone of proximal development—to stretch what the child can do with a little assistance (see Box 4.1 above). As the child advances, so does the level of collaboration demanded by the mother. The mother systematically shapes their joint experiences in such a way that the child will be drawn into taking more and more responsibility for their joint work. In so doing, she not only provides an excellent learning environment, she also models appropriate comprehension-fostering activities; crucial regulatory activities are thereby made overt and explicit.

Story telling is a powerful way to organize lived and listened-to experiences, and it provides an entry into the ability to construe narrative from text. By the time children are 3 or 4, they are beginning narrators; they can tell many kinds of stories, including relating autobiographical events, retelling fiction, and recalling stories they have heard. The everyday experiences of children foster this story telling. Children like to talk and learn about familiar activities, scripts or schemes, the "going to bed" script or the "going to McDonald's" script (Nelson, 1986; Mandler, 1996). Children like to listen to and retell personal experiences. These reminiscences are stepping stones to more mature narratives. As they get older, children increase their levels of participation by adding elements to the story and taking on greater pieces of the authorial responsibility. By 3 years of age, children in families in which joint story telling is common can take over the leadership role in constructing personal narratives.

Reminiscing also enables children to relate upsetting experiences; such narratives act as "cooling vessels" (Bruner, 1972), distancing the experience and confirming the safe haven of homes and other supportive environments. This early interest in sharing experience, joint picture book reading, and narrative, in general, have obvious implications for literary appreciation in preschool and early grades. Indeed, the KEEP (Au, 1981; Au and Jordan, 1981) program in Hawaii and the Reciprocal Teaching Program (Palinscar and Brown, 1984) in urban U.S. cities were both explicitly modeled after the natural interactions; they attempted to build on them and model the style. Connection-making and scaffolding by parents to support children's mathematical learning has also proved a successful intervention (Saxe et al., 1984; Byrnes, 1996) that has been mimicked in school settings.

Cultural Variations in Communication

There are great cultural variations in the ways in which adults and children communicate, and there are wide individual differences in communication styles within any cultural community. All cultural variations provide strong supports for children's development. However, some variations are more likely than others to encourage development of the specific kinds of knowledge and interaction styles that are expected in typical U.S. school environments. It is extremely important for educators—and parents—to take these differences into account.

Conversing, Observing, or Eavesdropping

In some communities, children are seldom direct conversational partners with adults, but rather engage with adults by participating in adult activities. In such situations, children's learning occurs through observing adults and from the pointers and support provided by adults in the contexts of ongoing activities. Such engagements contrast sharply with patterns common in other communities, in which adults take the role of directly instructing young children in language and other skills through explicit lessons that are not embedded in the contexts of ongoing activities (Ochs and Schieffelin, 1984; Rogoff, 1990; Rogoff et al., 1993).

For example, Pueblo Indian children are provided access to many aspects of adult life and are free to choose how and with whom to participate (John-Steiner, 1984). Their reports of their own learning stress their role as "apprentices" to more experienced members of the community (Suina and Smolkin, 1994). Observation and verbal explanation occur in the contexts of involvement in the processes as they are being learned.

In an African-American community of Louisiana, in which children are expected to be "seen and not heard," language learning occurs by eavesdropping. "The silent absorption in community life, the participation in the daily commercial rituals, and the hours spent overhearing adults' conversations should not be underestimated in their impact on a child's language growth" (Ward, 1971:37). "Nothing is censored for children's ears; they go everywhere in the community except Saturday-night parties." Older children teach social and intellectual skills: "Alphabets, colors, numbers, rhymes, word games, pen and pencil games are learned . . . from older children. No child, even the firstborn, is without such tutelage, since cousins, aunts, and uncles of their own age and older are always on hand" (Ward, 1971:25).

In this community, small children are not conversational partners with adults, as in the sense of other people with whom one converses. If children have something important to say, parents will listen, and children had better listen when their parents speak to them. But for conversation, adults talk to adults. Questions between older children and adults involve straightforward requests for information, not questions asked for the sake of conversation or for parents to drill children on topics to which the parents already know the answers. Mothers' speech to children, while not taking the form of a dialogue, is carefully regularized, providing precise, workable models of the language used in the community (Ward, 1971).

Schooling and the Role of Questioning

Detailed ethnographic research studies have shown striking differences in how adults and children interact verbally. Because of the prevalence of the use of questions in classrooms, one particularly important difference is how people treat questions and answers. One classic study, a comparison between the questioning behavior of white middle-class teachers in their own homes and the home question interaction of their working-class African-American pupils, showed dramatic differences (Heath, 1981, 1983). The middle-class mothers began the questioning game almost from birth and well before a child could be expected to answer. For example, a mother questions her 8-week-old infant, "You want your teddy bear?" and responds for the child, "Yes, you want your bear" (see Box 4.6 above). These rituals set the stage for a general reliance on questioning and pseudo-questioning interactions that serve a variety of social functions. Children exposed to these interaction patterns seem compelled to provide an answer and are quite happy to provide information that they know perfectly well an adult already possesses.

Such "known-answer" questions, where the interrogator has the information being requested, occur frequently in classroom dialogues (Mehan, 1979). Teachers routinely call on children to answer questions that serve to display and practice their knowledge, rather than to provide information that the teacher does not know. Similarly, in middle-class homes, known-answer questions predominate. For example, in one 48-hour period, almost half the utterances (48% of 215) addressed to 27-month-old Missy were questions; of these questions, almost half (46%) were known-answer questions (Heath, 1981, 1983).

In general, questions played a less central role in the home social interaction patterns of the African-American children; in particular, there was a notable lack of known-answer rituals (Heath, 1981, 1983). The verbal interactions served a different function, and they were embedded within different communicative and interpersonal contexts. Common questioning forms were analogy, story-starting, and accusatory; these forms rarely occurred in the white homes. For example, the African-American children were commonly asked to engage in the sophisticated use of metaphors by responding to questions that asked for analogical comparisons. The children were more likely to be asked "What's that like?" or "Who's he acting like?" rather than "What's that?" Such questions reflected the African-American adults' assumptions that preschool children are adept at noting likenesses between things, assumptions that are also revealed in speech forms other than questioning, such as frequent use of similes and metaphors. The adults were asked about and value metaphorical thinking and narrative exposition initiated by a storytelling question: one participant indicated a willingness to tell a story using the question form, "Did you see Maggie's dog yesterday?" The appropriate answer to such a query is not "yes" or "no," but another question, "No, what happened to Maggie's dog yesterday?" that sets the stage for the initiator's narrative. Both adults and older preschool children were totally familiar with these questioning rituals and played them enthusiastically.

These examples emphasize the systematic differences between the form and function of questioning behaviors in the working-class black and middle-class white communities that were studied. Neither approach is "deficient," but the match between the activities that predominate in classrooms at the early grades is much greater with middle-class homes than with working-class ones in that community. As the middle-class teachers practiced their familiar questioning routines with their pupils, it is not surprising that the middle-class pupils, who shared the teacher's background, successfully fulfilled the answerer role, while the working-class African-American children were often perplexed (Heath, 1981, 1983). Moreover, teachers were sometimes bewildered by what they regarded as the lack of responsible answering behavior on the part of their black pupils. They commented (Heath, 1981:108):

> They don't seem to be able to answer even the simplest questions.
>
> I would almost think some of them have a hearing problem; it is as though they don't hear me ask a question. I get blank stares to my question. When I am making statements or telling stories which interest them, they always seem to hear me.
>
> The simplest questions are the ones they can't answer in the classroom; yet on the playground, they can explain a rule for a ballgame, etc. They can't be as dumb as they seem in my class.
>
> I sometimes feel that when I look at them and ask a question I'm staring at a wall I can't break through.

However, as the teachers learned about the types of metaphoric and narrative question sequences with which the children are familiar, they were able to gradually introduce the unfamiliar known-answer routines. This is an excellent example of the "two-way path, from school to the community and from the community to school" (Heath, 1981:125) that is needed if the transition to formal schooling is to be made less traumatic for ethnically diverse groups. Not only can interventions be devised to help minority-culture parents prepare children for school, but the schools themselves can be sensitive to the problems of cultural mismatches. The answer is not to concentrate exclusively on changing children or changing schools, but to encourage adaptive flexibility in both directions.

CONCLUSION

The concept of "development" is critical to understanding the changes in children's thinking, such as the development of language, causal reasoning, and rudimentary mathematical concepts.

Young children are actively engaged in making sense of their worlds. In some particular domains, such as biological and physical causality, number, and language, they have strong predispositions to learn rapidly and readily. These predispositions support and may even make possible early learning and pave the way for competence in early schooling. Yet even in these domains, children still have a great deal of learning to do.

Children's early understanding of the perceptual and physical world may jump-start the learning process, even making learning possible, but one should look with caution for ways in which early knowledge may impede later learning. For example, children who treat rational numbers as they had treated whole numbers will experience trouble ahead. Awareness of these roadblocks to learning could help teachers anticipate the difficulty.

Although children learn readily in some domains, they can learn practically anything by sheer will and effort. When required to learn about nonprivileged domains they need to develop strategies of intentional learning. In order to develop strategic competence in learning, children need to understand what it means to learn, who they are as learners, and how to go about planning, monitoring, revising, and reflecting upon their learning and that of others. Children lack knowledge and experience but not reasoning ability. Although young children are inexperienced, they reason facilely with the knowledge they have.

Children are both problem solvers and problem generators: children attempt to solve problems presented to them, and they also seek novel challenges. They refine and improve their problem-solving strategies not only in the face of failure, but also by building on prior success. They persist because success and understanding are motivating in their own right.

Adults help make connections between new situations and familiar ones for children. Children's curiosity and persistence are supported by adults who direct their attention, structure their experiences, support their learning attempts, and regulate the complexity and difficulty levels of information for them.

Children, thus, exhibit capacities that are shaped by environmental experiences and the individuals who care for them. Caregivers provide supports, such as directing children's attention to critical aspects of events, commenting on features that should be noticed, and in many other ways providing structure to the information. Structure is critical for learning and for moving toward understanding information. Development and learning are not two parallel processes. Early biological underpinnings enable certain types of interactions, and through various environmental supports from caregivers and other cultural and social supports, a child's experiences for learning are expanded. Learning is promoted and regulated both by children's biology and ecology, and learning produces development.

5

Mind and Brain

As the popular press has discovered, people have a keen appetite for research information about how the brain works and how thought processes develop (*Newsweek*, 1996, 1997; *Time*, 1997a, b). Interest runs particularly high in stories about the neuro-development of babies and children and the effect of early experiences on learning. The fields of neuroscience and cognitive science are helping to satisfy this fundamental curiosity about how people think and learn.

In considering which findings from brain research are relevant to human learning or, by extension, to education, one must be careful to avoid adopting faddish concepts that have not been demonstrated to be of value in classroom practice. Among these is the concept that the left and right hemispheres of the brain should be taught separately to maximize the effectiveness of learning. Another is the notion that the brain grows in holistic "spurts," within or around which specific educational objectives should be arranged: as discussed in this chapter, there is significant evidence that brain regions develop asynchronously, although any specific educational implications of this remain to be determined. Another widely held misconception is that people use only 20 percent of their brains—with different percentage figures in different incarnations—and should be able to use more of it. This belief appears to have arisen from the early neuroscience finding that much of the cerebral cortex consists of "silent areas" that are not activated by sensory or motor activity. However, it is now known that these silent areas mediate higher cognitive functions that are not directly coupled to sensory or motor activity.

Advances in neuroscience are confirming theoretical positions advanced by developmental psychology for a number of years, such as the importance of early experience in development (Hunt, 1961). What is new, and therefore important for this volume, is the *convergence* of evidence from a number of scientific fields. As the sciences of developmental psychology, cognitive psychology, and neuroscience, to name but three, have contributed vast numbers of research studies, details about learning and development have converged to form a more complete picture of how intellectual development occurs. Clarification of some of the mechanisms of learning by neuroscience has been advanced, in part, by the advent of non-invasive imaging technologies, such as positron emission tomography (PET) and functional magnetic resonance imaging (FMRI). These technologies have allowed researchers to observe human learning processes directly.

This chapter reviews key findings from neuroscience and cognitive science that are expanding knowledge of the mechanisms of human learning. Three main points guide the discussion in this chapter:

1. Learning changes the physical structure of the brain.
2. These structural changes alter the functional organization of the brain; in other words, learning organizes and reorganizes the brain.
3. Different parts of the brain may be ready to learn at different times.

We first explain some basic concepts of neuroscience and new knowledge about brain development, including the effects of instruction and learning on the brain. We then look at language in learning as an example of the mind-brain connection. Lastly, we examine research on how memory is represented in the brain and its implications for learning.

From a neuroscience perspective, instruction and learning are very important parts of a child's brain development and psychological development processes. Brain development and psychological development involve continuous interactions between a child and the external environment—or, more accurately, a hierarchy of environments, extending from the level of the individual body cells to the most obvious boundary of the skin. Greater understanding of the nature of this interactive process renders moot such questions as how much depends on genes and how much on environment. As various developmental researchers have suggested, this question is much like asking which contributes most to the area of a rectangle, its height or its width (Eisenberg, 1995)?

THE BRAIN: FOUNDATION FOR LEARNING

Neuroscientists study the anatomy, physiology, chemistry, and molecular biology of the nervous system, with particular interest in how brain activity relates to behavior and learning. Several crucial questions about early learning particularly intrigue neuroscientists. How does the brain develop? Are there stages of brain development? Are there critical periods when certain things must happen for the brain to develop normally? How is information encoded in the developing and the adult nervous systems? And perhaps most important: How does experience affect the brain?

Some Basics

A nerve cell, or neuron, is a cell that receives information from other nerve cells or from the sensory organs and then projects that information to other nerve cells, while still other neurons project it back to the parts of the body that interact with the environment, such as the muscles. Nerve cells are equipped with a cell body—a sort of metabolic heart—and an enormous treelike structure called the dendritic field, which is the input side of the neuron. Information comes into the cell from projections called axons. Most of the excitatory information comes into the cell from the dendritic field, often through tiny dendritic projections called spines. The junctions through which information passes from one neuron to another are called synapses, which can be excitatory or inhibitory in nature. The neuron integrates the information it receives from all of its synapses and this determines its output.

During the development process, the "wiring diagram" of the brain is created through the formation of synapses. At birth, the human brain has in place only a relatively small proportion of the trillions of synapses it will eventually have; it gains about two-thirds of its adult size after birth. The rest of the synapses are formed after birth, and a portion of this process is guided by experience.

Synaptic connections are added to the brain in two basic ways. The first way is that synapses are overproduced, then selectively lost. Synapse overproduction and loss is a fundamental mechanism that the brain uses to incorporate information from experience. It tends to occur during the early periods of development. In the visual cortex—the area of the cerebral cortex of the brain that controls sight—a person has many more synapses at 6 months of age than at adulthood. This is because more and more synapses are formed in the early months of life, then they disappear, sometimes in prodigious numbers. The time required for this phenomenon to run its course varies in different parts of the brain, from 2 to 3 years in the human visual cortex to 8 to 10 years in some parts of the frontal cortex.

Some neuroscientists explain synapse formation by analogy to the art of sculpture. Classical artists working in marble created a sculpture by chiseling away unnecessary bits of stone until they achieved their final form. Animal studies suggest that the "pruning" that occurs during synapse overproduction and loss is similar to this act of carving a sculpture. The nervous system sets up a large number of connections; experience then plays on this network, selecting the appropriate connections and removing the inappropriate ones. What remains is a refined final form that constitutes the sensory and perhaps the cognitive bases for the later phases of development.

The second method of synapse formation is through the addition of new synapses—like the artist who creates a sculpture by adding things together until the form is complete. Unlike synapse overproduction and loss, the process of synapse addition operates throughout the entire human life span and is especially important in later life. This process is not only sensitive to experience, it is actually driven by experience. Synapse addition probably lies at the base of some, or even most, forms of memory. As discussed later in this chapter, the work of cognitive scientists and education researchers is contributing to our understanding of synapse addition.

Wiring the Brain

The role of experience in wiring the brain has been illuminated by research on the visual cortex in animals and humans. In adults, the inputs entering the brain from the two eyes terminate separately in adjacent regions of the visual cortex. Subsequently, the two inputs converge on the next set of neurons. People are not born with this neural pattern. But through the normal processes of seeing, the brain sorts things out.

Neuroscientists discovered this phenomenon by studying humans with visual abnormalities, such as a cataract or a muscle irregularity that deviates the eye. If the eye is deprived of the appropriate visual experience at an early stage of development (because of such abnormalities), it loses its ability to transmit visual information into the central nervous system. When the eye that was incapable of seeing at a very early age was corrected later, the correction alone did not help—the afflicted eye still could not see. When researchers looked at the brains of monkeys in which similar kinds of experimental manipulations had been made, they found that the normal eye had captured a larger than average amount of neurons, and the impeded eye had correspondingly lost those connections.

This phenomenon only occurs if an eye is prevented from experiencing normal vision very early in development. The period at which the eye is sensitive corresponds to the time of synapse overproduction and loss in the visual cortex. Out of the initial mix of overlapping inputs, the neural connections that belong to the eye that sees normally tend to survive, while the connections that belong to the abnormal eye wither away. When both eyes see normally, each eye loses some of the overlapping connections, but both keep a normal number.

In the case of deprivation from birth, one eye completely takes over. The later the deprivation occurs after birth, the less effect it has. By about 6 months of age, closing one eye for weeks on end will produce no effect whatsoever. The critical period has passed; the connections have already sorted themselves out, and the overlapping connections have been eliminated.

This anomaly has helped scientists gain insights into normal visual development. In normal development, the pathway for each eye is sculpted (or "pruned") down to the right number of connections, and those connections are sculpted in other ways, for example, to allow one to see patterns. By overproducing synapses then selecting the right connections, the brain develops an organized wiring diagram that functions optimally. The brain development process actually uses visual information entering from outside to become more precisely organized than it could with intrinsic molecular mechanisms alone. This external information is even more important for later cognitive development. The more a person interacts with the world, the more a person needs information from the world incorporated into the brain structures.

Synapse overproduction and selection may progress at different rates in different parts of the brain (Huttenlocher and Dabholkar, 1997). In the primary visual cortex, a peak in synapse density occurs relatively quickly. In the medial frontal cortex, a region clearly associated with higher cognitive functions, the process is more protracted: synapse production starts before birth and synapse density continues to increase until 5 or 6 years of age. The selection process, which corresponds conceptually to the main organization of patterns, continues during the next 4-5 years and ends around early adolescence. This lack of synchrony among cortical regions may also occur upon individual cortical neurons where different inputs may mature at different rates (see Juraska, 1982, on animal studies).

After the cycle of synapse overproduction and selection has run its course, additional changes occur in the brain. They appear to include both the modification of existing synapses and the addition of entirely new synapses to the brain. Research evidence (described in the next section) suggests that activity in the nervous system associated with learning experiences somehow causes nerve cells to create new synapses. Unlike the process of synapse overproduction and loss, synapse addition and modification are lifelong processes, driven by experience. In essence, the quality of information to which one is exposed and the amount of information one acquires is reflected throughout one's life in the structure of the brain. This process is probably not the only way that information is stored in the brain, but it is a very important way that provides insight into how people learn.

EXPERIENCES AND ENVIRONMENTS FOR BRAIN DEVELOPMENT

Alterations in the brain that occur during learning seem to make the nerve cells more efficient or powerful. Animals raised in complex environments have a greater volume of capillaries per nerve cell—and therefore a greater supply of blood to the brain—than the caged animals, regardless of whether the caged animal lived alone or with companions (Black et al., 1987). (Capillaries are the tiny blood vessels that supply oxygen and other nutrients to the brain.) In this way experience increases the overall quality of functioning of the brain. Using astrocytes (cells that support neuron functioning by providing nutrients and removing waste) as the index, there are higher amounts of astrocyte per neuron in the complex-environment animals than in the caged groups. Overall, these studies depict an orchestrated pattern of increased capacity in the brain that depends on experience.

Other studies of animals show other changes in the brain through learning; see Box 5.1. The weight and thickness of the cerebral cortex can be measurably altered in rats that are reared from weaning, or placed as adults, in a large cage enriched by the presence both of a changing set of objects for play and exploration and of other rats to induce play and exploration (Rosenzweig and Bennett, 1978). These animals also perform better on a variety of problem-solving tasks than rats reared in standard laboratory cages. Interestingly, both the interactive presence of a social group and direct physical contact with the environment are important factors: animals placed in the enriched environment alone showed relatively little benefit; neither did animals placed in small cages within the larger environment (Ferchmin et al., 1978; Rosenzweig and Bennett, 1972). Thus, the gross structure of the cerebral cortex was altered both by exposure to opportunities for learning and by learning in a social context.

Does Mere Neural Activity Change the Brain or Is Learning Required?

Are the changes in the brain due to actual learning or to variations in aggregate levels of neural activity? Animals in a complex environment not only learn from experiences, but they also run, play, and exercise, which activates the brain. The question is whether activation alone can produce brain changes without the subjects actually learning anything, just as activation of muscles by exercise can cause them to grow. To answer this question, a group of animals that learned challenging motor skills but had relatively little brain activity was compared with groups that had high levels of brain activity but did relatively little learning (Black et al., 1990). There were four groups in all. One group of rats was taught to traverse an elevated obstacle course; these "acrobats" became very good at the task over a month or so of practice. A second group of "mandatory exercisers" was put on a treadmill once a day, where they ran for 30 minutes, rested for 10 minutes, then ran another 30 minutes. A third group of "voluntary exercisers" had free access to an activity wheel attached directly to their cage, which they used often. A control group of "cage potato" rats had no exercise.

What happened to the volume of blood vessels and number of synapses per neuron in the rats? Both the mandatory exercisers and the voluntary exercisers showed higher densities of blood vessels than either the cage potato rats or the acrobats, who learned skills that did not involve significant

BOX 5.1 Making Rats Smarter

How do rats learn? Can rats be "educated?" In classic studies, rats are placed in a complex communal environment filled with objects that provide ample opportunities for exploration and play (Greenough, 1976). The objects are changed and rearranged each day, and during the changing time, the animals are put in yet another environment with another set of objects. So, like their real-world counterparts in the sewers of New York or the fields of Kansas, these rats have a relatively rich set of experiences from which to draw information. A contrasting group of rats is placed in a more typical laboratory environment, living alone or with one or two others in a barren cage—which is obviously a poor model of a rat's real world. These two settings can help determine how experience affects the development of the normal brain and normal cognitive structures, and one can also see what happens when animals are deprived of critical experiences.

After living in the complex or impoverished environments for a period from weaning to rat adolescence, the two groups of animals were subjected to a learning experience. The rats that had grown up in the complex environment made fewer errors at the outset than the other rats; they also learned more quickly not to make any errors at all. In this sense, they were smarter than their more deprived counterparts. And with positive rewards, they performed better on complex tasks than the animals raised in individual cages. Most significant, learning altered the rats' brains: the animals from the complex environment had 20-25 percent more synapses per nerve cell in the visual cortex than the animals from the standard cages (see Turner and Greenough, 1985; Beaulieu and Colonnier, 1987). It is clear that when animals learn, they add new connections to the wiring of their brains—a phenomenon not limited to early development (see, e.g., Greenough et al., 1979).

amounts of activity. But when the number of synapses per nerve cell was measured, the acrobats were the standout group. Learning adds synapses; exercise does not. Thus, different kinds of experience condition the brain in different ways. Synapse formation and blood vessel formation (vascularization) are two important forms of brain adaptation, but they are driven by different physiological mechanisms and by different behavioral events.

Localized Changes

Learning specific tasks brings about localized changes in the areas of the brain appropriate to the task. For example, when young adult animals were taught a maze, structural changes occurred in the visual area of the cerebral cortex (Greenough et al., 1979). When they learned the maze with one eye blocked with an opaque contact lens, only the brain regions connected to the open eye were altered (Chang and Greenough, 1982). When they learned a set of complex motor skills, structural changes occurred in the motor region of the cerebral cortex and in the cerebellum, a hindbrain structure that coordinates motor activity (Black et al., 1990; Kleim et al., 1996).

These changes in brain structure underlie changes in the functional organization of the brain. That is, learning imposes new patterns of organization on the brain, and this phenomenon has been confirmed by electrophysiological recordings of the activity of nerve cells (Beaulieu and Cynader, 1990). Studies of brain development provide a model of the learning process at a cellular level: the changes first observed in rats have also proved to be true in mice, cats, monkeys, and birds, and they almost certainly occur in humans.

ROLE OF INSTRUCTION IN BRAIN DEVELOPMENT

Clearly, the brain can store information, but what kinds of information? The neuroscientist does not address these questions. Answering them is the job of cognitive scientists, education researchers, and others who study the effects of experiences on human behavior and human potential. Several examples illustrate how instruction in specific kinds of information can influence natural development processes. This section discusses a case involving language development.

Language and Brain Development

Brain development is often timed to take advantage of particular experiences, such that information from the environment helps to organize the brain. The development of language in humans is an example of a natural process that is guided by a timetable with certain limiting conditions. Like the development of the visual system, parallel processes occur in human language development for the capacity to perceive phonemes, the “atoms” of speech. A phoneme is defined as the smallest meaningful unit of speech sound. Human beings discriminate the “b” sound from the “p” sound largely by perceiving the time of the onset of the voice relative to the time the lips part; there is a boundary that separates “b” from “p” that helps to distinguish “bet” from “pet.” Boundaries of this sort exist among closely related phonemes, and in adults these boundaries reflect language experience. Very young children discriminate many more phonemic boundaries than adults, but they lose their discriminatory powers when certain boundaries are not supported by experience with spoken language (Kuhl, 1993). Native Japanese speakers, for example, typically do not discriminate the "r" from the "l" sounds that are evident to English speakers, and this ability is lost in early childhood because it is not in the speech that they hear. It is not known whether synapse overproduction and elimination underlies this process, but it certainly seems plausible.

The process of synapse elimination occurs relatively slowly in the cerebral cortical regions that are involved in aspects of language and other higher cognitive functions (Huttenlocher and Dabholkar, 1997). Different brain systems appear to develop according to different time frames, driven in part by experience and in part by intrinsic forces. This process suggests that children's brains may be more ready to learn different things at different times. But, as noted above, learning continues to affect the structure of the brain long after synapse overproduction and loss are completed. New synapses are added that would never have existed without learning, and the wiring diagram of the brain continues to be reorganized throughout one's life. There may be other changes in the brain involved in the encoding of learning, but most scientists agree that synapse addition and modification are the ones that are most certain.

Examples of Effects of Instruction on Brain Development

Detailed knowledge of the brain processes that underlie language has emerged in recent years. For example, there appear to be separate brain areas that specialize in subtasks such as hearing words (spoken language of others), seeing words (reading), speaking words (speech), and generating words (thinking with language). Whether these patterns of brain organization for oral, written, and listening skills require separate exercises to promote the component skills of language and literacy remains to be determined. If these closely related skills have somewhat independent brain representation, then coordinated practice of skills may be a better way to encourage learners to move seamlessly among speaking, writing, and listening.

Language provides a particularly striking example of how instructional processes may contribute to organizing brain functions. The example is interesting because language processes are usually more closely associated with the left side of the brain. As the following discussion points out, specific kinds of experiences can contribute to other areas of the brain taking over some of the language functions. For example, deaf people who learn a sign language are learning to communicate using the visual system in place of the auditory system. Manual sign languages have grammatical structures, with affixes and morphology, but they are not translations of spoken languages. Each particular sign language (such as American Sign Language) has a unique organization, influenced by the fact that it is perceived visually. The perception of sign language depends on parallel visual perception of shape, relative spatial location, and movement of the hands—a very different type of perception than the auditory perception of spoken language (Bellugi, 1980).

In the nervous system of a hearing person, auditory system pathways appear to be closely connected to the brain regions that process the features of spoken language, while visual pathways appear to go through several stages of processing before features of written language are extracted (Blakemore, 1977; Friedman and Cocking, 1986). When a deaf individual learns to communicate with manual signs, different nervous system processes have replaced the ones normally used for language—a significant achievement.

Neuroscientists have investigated how the visual-spatial and language processing areas each come together in a different hemisphere of the brain, while developing certain new functions as a result of the visual language experiences. In the brains of all deaf people, some cortical areas that normally process auditory information become organized to process visual information. Yet there are also demonstrable differences among the brains of deaf people who use sign language and deaf people who do not use sign language, presumably because they have had different language experiences (Neville, 1984, 1995). Among other things, major differences exist in the electrical activities of the brains of deaf individuals who use sign language and those who do not know sign language (Friedman and Cocking, 1986; Neville, 1984). Also, there are similarities between sign language users with normal hearing and sign language users who are deaf that result from their common experiences of engaging in language activities. In other words, specific types of instruction can modify the brain, enabling it to use alternative sensory input to accomplish adaptive functions, in this case, communication.

Another demonstration that the human brain can be functionally reorganized by instruction comes from research on individuals who have suffered strokes or had portions of the brain removed (Bach-y-Rita, 1980, 1981; Crill and Raichle, 1982). Since spontaneous recovery is generally unlikely, the best way to help these individuals regain their lost functions is to provide them with instruction and long periods of practice. Although this kind of learning typically takes a long time, it can lead to partial or total recovery of functions when based on sound principles of instruction. Studies of animals with similar impairments have clearly shown the formation of new brain connections and other adjustments, not unlike those that occur when adults learn (e.g., Jones and Schallert, 1994; Kolb, 1995). Thus, guided learning and learning from individual experiences both play important roles in the functional reorganization of the brain.

MEMORY AND BRAIN PROCESSES

Research into memory processes has progressed in recent years through the combined efforts of neuroscientists and cognitive scientists, aided by positron emission tomography and functional magnetic resonance imaging (Schacter, 1997). Most of the research advances in memory that help scientists understand learning come from two major groups of studies: studies that show that memory is not a unitary construct and studies that relate features of learning to later effectiveness in recall.

Memory is neither a single entity nor a phenomenon that occurs in a single area of the brain. There are two basic memory processes: declarative memory, or memory for facts and events which occurs primarily in brain systems involving the hippocampus; and procedural or nondeclarative memory, which is memory for skills and other cognitive operations, or memory that cannot be represented in declarative sentences, which occurs principally in the brain systems involving the neostriatum (Squire, 1997).

Different features of learning contribute to the durability or fragility of memory. For example, comparisons of people's memories for words with their memories for pictures of the same objects show a superiority effect for pictures. The superiority effect of pictures is also true if words and pictures are combined during learning (Roediger, 1997). Obviously, this finding has direct relevance for improving the long-term learning of certain kinds of information.

Research has also indicated that the mind is not just a passive recorder of events, rather, it is actively at work both in storing and in recalling information. There is research demonstrating that when a series of events are presented in a random sequence, people reorder them into sequences that make sense when they try to recall them (Lichtenstein and Brewer, 1980). The phenomenon of the active brain is dramatically illustrated further by the fact that the mind can "remember" things that actually did not happen. In one example (Roediger, 1997), people are first given lists of words: sour-candy-sugar-bitter-good-taste-tooth-knife-honey-photo-chocolate-heart-cake-tart-pie. During the later recognition phase, subjects are asked to respond "yes" or "no" to questions of whether a particular word was on the list. With high frequency and high reliability, subjects report that the word "sweet" was on the list. That is, they "remember" something that is not correct. The finding illustrates the active mind at work using inferencing processes to relate events. People "remember" words that are implied but not stated with the same probability as learned words. In an act of efficiency and "cognitive economy" (Gibson, 1969), the mind creates categories for processing information. Thus, it is a feature of learning that memory processes make relational links to other information.

In view of the fact that experience alters brain structures and that specific experiences have specific effects on the brain, the nature of "experience" becomes an interesting question in relation to memory processes. For example, when children are asked if a false event has ever occurred (as verified by their parents), they will correctly say that it never happened to them (Ceci, 1997). However, after repeated discussions around the same false events spread over time, the children begin to identify these false events as true occurrences. After about 12 weeks of such discussions, children give fully elaborated accounts of these fictitious events, involving parents, siblings, and a whole host of supporting "evidence." Repeating lists of words with adults similarly reveals that recalling non-experienced events activates the same regions of the brain as events or words that were directly experienced (Schacter, 1997). Magnetic resonance imaging also shows that the same brain areas are activated during questions and answers about both true and false events. This may explain why false memories can seem so compelling to the individual reporting the events.

In sum, classes of words, pictures, and other categories of information that involve complex cognitive processing on a repeated basis activate the brain. Activation sets into motion the events that are encoded as part of long-term memory. Memory processes treat both true and false memory events similarly and, as shown by imaging technologies, activate the same brain regions, regardless of the validity of what is being remembered. Experience is important for the development of brain structures, and what is registered in the brain as memories of experiences can include one's own mental activities.

These points about memory are important for understanding learning and can explain a good deal about why experiences are remembered well or poorly. Particularly important is the finding that the mind imposes structure on the information available from experience. This parallels descriptions of the organization of information in skilled performance discussed in Chapter 3: one of the primary differences between the novice and the expert is the manner in which information is organized and utilized. From the perspective of teaching, it again suggests the importance of an appropriate overall framework within which learning occurs most efficiently and effectively (see evidence discussed in Chapters 3 and 4).

Overall, neuroscience research confirms the important role that experience plays in building the structure of the mind by modifying the structures of the brain: development is not solely the unfolding of preprogrammed patterns. Moreover, there is a convergence of many kinds of research on some of the rules that govern learning. One of the simplest rules is that practice increases learning; in the brain, there is a similar relationship between the amount of experience in a complex environment and the amount of structural change.

In summary, neuroscience is beginning to provide some insights, if not final answers, to questions of great interest to educators. There is growing evidence that both the developing and the mature brain are structurally altered when learning occurs. Thus, these structural changes are believed to encode the learning in the brain. Studies have found alterations in the weight and thickness of the cerebral cortex of rats that had direct contact with a stimulating physical environment and an interactive social group. Subsequent work has revealed underlying changes in the structure of nerve cells and of the tissues that support their function. The nerve cells have a greater number of the synapses through which they communicate with each other. The structure of the nerve cells themselves is correspondingly altered. Under at least some conditions, both astrocytes that provide support to the neurons and the capillaries that supply blood may also be altered. The learning of specific tasks appears to alter the specific regions of the brain involved in the task. These findings suggest that the brain is a dynamic organ, shaped to a great extent by experience—by what a living being does, and has done.

CONCLUSION

It is often popularly argued that advances in the understanding of brain development and mechanisms of learning have substantial implications for education and the learning sciences. In addition, certain brain scientists have offered advice, often with a tenuous scientific basis, that has been incorporated into publications designed for educators (see, e.g., Sylwester, 1995:Ch. 7). Neuroscience has advanced to the point where it is time to think critically about the form in which research information is made available to educators so that it is interpreted appropriately for practice—identifying which research findings are ready for implementation and which are not.

This chapter reviews the evidence for the effects of experience on brain development, the adaptability of the brain for alternative pathways to learning, and the impact of experience on memory. Several findings about the brain and the mind are clear and lead to the next research topics:

1. The functional organization of the brain and the mind depends on and benefits positively from experience.

2. Development is not merely a biologically driven unfolding process, but also an active process that derives essential information from experience.

3. Research has shown that some experiences have the most powerful effects during specific sensitive periods, while others can affect the brain over a much longer time span.

4. An important issue that needs to be determined in relation to educa-

tion is which things are tied to critical periods (e.g., some aspects of phonemic perception and language learning) and for which things is the time of exposure less critical.

From these findings, it is clear that there are qualitative differences among kinds of learning opportunities. In addition, the brain "creates" informational experiences through mental activities such as inferencing, category formation, and so forth. These are types of learning opportunities that can be facilitated. By contrast, it is a bridge too far, to paraphrase John Bruer (1997), to suggest that specific activities lead to neural branching (Cardellichio and Field, 1997), as some interpreters of neuroscience have implied.

III

TEACHERS AND TEACHING

6

The Design of Learning Environments

In this chapter we discuss implications of new knowledge about learning for the design of learning environments, especially schools. Learning theory does not provide a simple recipe for designing effective learning environments; similarly, physics constrains but does not dictate how to build a bridge (e.g., Simon, 1969). Nevertheless, new developments in the science of learning raise important questions about the design of learning environments—questions that suggest the value of rethinking what is taught, how it is taught, and how it is assessed. The focus in this chapter is on general characteristics of learning environments that need to be examined in light of new developments in the science of learning; Chapter 7 provides specific examples of instruction in the areas of mathematics, science, and history—examples that make the arguments in the present chapter more concrete.

We begin our discussion of learning environments by revisiting a point made in Chapter 1—that the learning goals for schools have undergone major changes during the past century. Everyone expects much more from today's schools than was expected 100 years ago. A fundamental tenet of modern learning theory is that different kinds of learning goals require different approaches to instruction (Chapter 3); new goals for education require changes in opportunities to learn. After discussing changes in goals, we explore the design of learning environments from four perspectives that appear to be particularly important given current data about human learning, namely, the degree to which learning environments are learner centered, knowledge centered, assessment centered, and community centered. Later, we define these perspectives and explain how they relate to the preceding discussions in Chapters 1-4.

CHANGES IN EDUCATIONAL GOALS

As discussed in Chapter 1, educational goals for the twenty-first century are very different from the goals of earlier times. This shift is important to keep in mind when considering claims that schools are "getting worse." In many cases, schools seem to be functioning as well as ever, but the challenges and expectations have changed quite dramatically (e.g., Bruer, 1993; Resnick, 1987).

Consider the goals of schooling in the early 1800s. Instruction in writing focused on the mechanics of making notation as dictated by the teacher, transforming oral messages into written ones. It was not until the mid to late 1800s that writing began to be taught on a mass level in most European countries, and school children began to be asked to compose their own written texts. Even then, writing instruction was largely aimed at giving children the capacity to closely imitate very simple text forms. It was not until the 1930s that the idea emerged of primary school students expressing themselves in writing (Alcorta, 1994; Schneuwly, 1994). As in writing, it was not until relatively recently that analysis and interpretation of what is read became an expectation of skilled reading by all school children. Overall, the definition of functional literacy changed from being able to sign one's name to word decoding to reading for new information (Resnick and Resnick, 1977); see Box 6.1.

In the early 1900s, the challenge of providing mass education was seen by many as analogous to mass production in factories. School administrators were eager to make use of the "scientific" organization of factories to structure efficient classrooms. Children were regarded as raw materials to be efficiently processed by technical workers (the teachers) to reach the end product (Bennett and LeCompte, 1990; Callahan, 1962; Kliebard, 1975). This approach attempted to sort the raw materials (the children) so that they could be treated somewhat as an assembly line. Teachers were viewed as workers whose job was to carry out directives from their superiors—the efficiency experts of schooling (administrators and researchers).

The emulation of factory efficiency fostered the development of standardized tests for measurement of the "product," of clerical work by teachers to keep records of costs and progress (often at the expense of teaching), and of "management" of teaching by central district authorities who had little knowledge of educational practice or philosophy (Callahan, 1962). In short, the factory model affected the design of curriculum, instruction, and assessment in schools.

Today, students need to understand the current state of their knowledge and to build on it, improve it, and make decisions in the face of uncertainty (Talbert and McLaughlin, 1993). These two notions of knowledge were identified by John Dewey (1916) as "records" of previous cultural accomplishments and engagement in active processes as represented by the phrase "to do." For example, doing mathematics involves solving problems, abstracting, inventing, proving (see, e.g., Romberg, 1983). Doing history involves the construction and evaluation of historical documents (see, e.g., Wineberg, 1996). Doing science includes such activities as testing theories

BOX 6.1 Literacy: Then and Now

Colonists were literate enough if they could sign their name, or even an X, on deeds. When immigrants arrived in large numbers in the 1800s, educators urged schools to deliver "recitation literacy" to the foreign children who filled the schoolrooms. That literacy was the ability to hold a book and reel off memorized portions of basic American texts such as the opening paragraph of the Declaration of Independence, a part of the Gettysburg address, or some Bryant or Longfellow. With the coming of World War I, and the prospect of large numbers of men handling new equipment in foreign countries, Army testers redefined reading. Suddenly, to the dismay of men used to reading familiar passages, passing the army reading test meant being able to make sense, on the spot, of never-before-seen text. Currently, that kind of "extraction literacy," revolutionary in 1914, looks meager. Finding out who, what, when, where or how simply does not yield the inferences, questions, or ideas we now think of as defining full or "higher literacy." The idea of a classroom where young women, poor and minority students, and learning disabled students *all* read (not recite) and write about (not copy) Shakespeare or Steinbeck is a radical and hopeful departure from the long-running conception of literacy as serviceable skills for the many and generative, reflective reading and writing for the few (Wolf, 1988:1).

through experimentation and observation (e.g., Lehrer and Schauble, 1996a, b; Linn, 1992, 1994; Schwab, 1978). Society envisions graduates of school systems who can identify and solve problems and make contributions to society throughout their lifetime—who display the qualities of "adaptive expertise" discussed in Chapter 3. To achieve this vision requires rethinking what is taught, how teachers teach, and how what students learn is assessed.

The remainder of this chapter is organized around Figure 6.1, which illustrates four perspectives on learning environments that seem particularly important given the principles of learning discussed in earlier chapters. Although we discuss these perspectives separately, they need to be conceptualized as a system of interconnected components that mutually support one another (e.g., Brown and Campione, 1996); we first discuss each perspective separately and then describe how they interrelate.

LEARNER-CENTERED ENVIRONMENTS

We use the term "learner centered" to refer to environments that pay careful attention to the knowledge, skills, attitudes, and beliefs that learners bring to the educational setting. This term includes teaching practices that

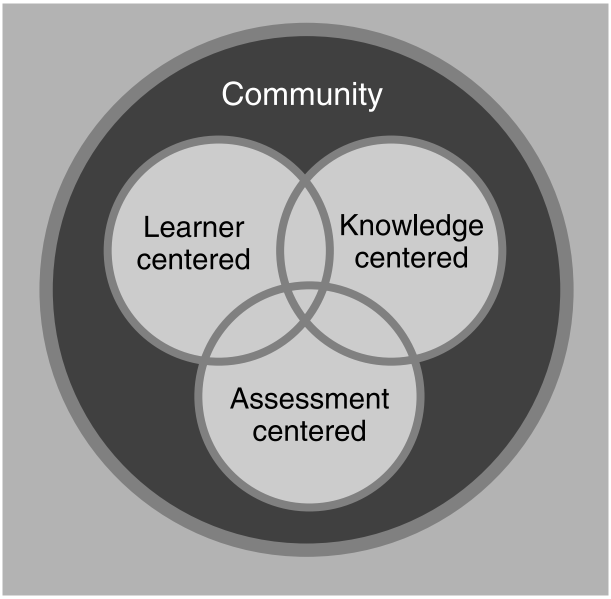


FIGURE 6.1 *Perspectives on learning environments. SOURCE: Bransford et al. (1998).*

have been called "culturally responsive," "culturally appropriate," "culturally compatible," and "culturally relevant" (Ladson-Billings, 1995). The term also fits the concept of "diagnostic teaching" (Bell et al., 1980): attempting to discover what students think in relation to the problems on hand, discussing their misconceptions sensitively, and giving them situations to go on thinking about which will enable them to readjust their ideas (Bell, 1982a:7). Teachers who are learner centered recognize the importance of building on the conceptual and cultural knowledge that students bring with them to the classroom (see Chapters 3 and 4).

Diagnostic teaching provides an example of starting from the structure of a child's knowledge. The information on which to base a diagnosis may be acquired through observation, questioning and conversation, and reflection on the products of student activity. A key strategy is to prompt children to explain and develop their knowledge structures by asking them to make predictions about various situations and explain the reasons for their predictions. By selecting critical tasks that embody known misconceptions, teachers can help students test their thinking and see how and why various ideas might need to change (Bell, 1982a, b, 1985; Bell et al., 1986; Bell and Purdy, 1985). The model is one of engaging students in cognitive conflict and then having discussions about conflicting viewpoints (see Piaget, 1973; Festinger, 1957). "To promote learning, it is important to focus on controlled changes of structure in a fixed context . . . or on deliberate transfer of a structure from one context to another" (Bell, 1985:72; see Chapter 7).

Learner-centered instruction also includes a sensitivity to the cultural practices of students and the effect of those practices on classroom learning. In a study of the Kamehameha School in Hawaii, teachers were deliberate in learning about students' home and community cultural practices and language use and incorporated them in classroom literacy instruction (Au and Jordan, 1981). After using the native Hawaiian "talk-story" (jointly produced student narratives), shifting the focus of instruction from decoding to comprehending, and including students' home experiences as a part of the discussion of reading materials, students demonstrated significant improvement in standardized test performance in reading.

Learner-centered teachers also respect the language practices of their students because they provide a basis for further learning. In science, one standard way of talking in both school and professional science is impersonal and expository, without any reference to personal or social intentions or experiences (Lemke, 1990; Wertsch, 1991). This way, which predominates in schools, privileges middle-class, mainstream ways of knowing and constitutes a barrier for students from other backgrounds who do not come to school already practiced in "school talk" (Heath, 1983). Everyday and scientific discourses need to be coordinated to assist students' scientific understanding.

In science discourse as it develops in most classrooms, students' talk frequently expresses multiple intentions or voices (see Ballenger, 1997; Bakhtin, 1984; Warren and Rosebery, 1996; Wertsch, 1991). In their narratives and arguments, students express both scientific and social intentions: scientific in that the students present evidence in support of a scientific argument; social in that they also talk about themselves as certain types of people (e.g., virtuous, honest, trustworthy). If the responses of other students and the teacher to these multivoiced narratives are always keyed to the scientific point, it helps to shape the meaning that is taken from them and relates them back to the context of the unfolding scientific argument (Ballenger, 1997). In standard science lessons, the scientific point in the talk of many students, particularly those whose discourse is not mainstream, is often missed, and the social intention is often devalued (Lemke, 1990; Michaels and Bruce, 1989; Wertsch, 1991; see Chapter 7).

In another example of connecting everyday talk and school talk, African American high school students were shown that many of their forms of everyday speech were examples of a very high form of literacy that was taught in school, but never before connected with their everyday experience (Lee, 1991, 1992). Like Proust who discovered he had been speaking prose all of his life, the students discovered that they were fluent in a set of competencies that were considered academically advanced.

Overall, learner-centered environments include teachers who are aware that learners construct their own meanings, beginning with the beliefs, understandings, and cultural practices they bring to the classroom. If teaching is conceived as constructing a bridge between the subject matter and the student, learner-centered teachers keep a constant eye on both ends of the bridge. The teachers attempt to get a sense of what students know and can do as well as their interests and passions—what each student knows, cares about, is able to do, and wants to do. Accomplished teachers "give learners reason," by respecting and understanding learners' prior experiences and understandings, assuming that these can serve as a foundation on which to build bridges to new understandings (Duckworth, 1987). Chapter 7 illustrates how these bridges can be built.

KNOWLEDGE-CENTERED ENVIRONMENTS

Environments that are solely learner centered would not necessarily help students acquire the knowledge and skills necessary to function effectively in society. As noted in Chapter 2, the ability of experts to think and solve problems is not simply due to a generic set of "thinking skills" or strategies but, instead, requires well-organized bodies of knowledge that support planning and strategic thinking. Knowledge-centered environments take seriously the need to help students become knowledgeable (Bruner, 1981) by learning in ways that lead to understanding and subsequent transfer. Current knowledge on learning and transfer (Chapter 3) and development (Chapter 4) provide important guidelines for achieving these goals. Standards in areas such as mathematics and science help define the knowledge and competencies that students need to acquire (e.g., American Association for the Advancement of Science, 1989; National Council of Teachers of Mathematics, 1989; National Research Council, 1996).

Knowledge-centered environments intersect with learner-centered environments when instruction begins with a concern for students' initial preconceptions about the subject matter. The story *Fish Is Fish* (Chapter 1) illustrates how people construct new knowledge based on their current knowledge. Without carefully considering the knowledge that students' bring to the learning situation, it is difficult to predict what they will understand about new information that is presented to them (see Chapters 3 and 4).

Knowledge-centered environments also focus on the kinds of information and activities that help students develop an understanding of disciplines (e.g., Prawat et al., 1992). This focus requires a critical examination of existing curricula. In history, a widely used history text on the American Revolution left out crucial information necessary to understand rather than merely memorize (Beck et al., 1989, 1991). In science, existing curricula tend to overemphasize facts and underemphasize "doing science" to explore and test big ideas (American Association for the Advancement of Science, 1989; National Research Council, 1996). As noted in Chapter 2, the Third International Mathematics and Science Study (Schmidt et al., 1997) characterized American curricula in mathematics and science as being "a mile wide and an inch deep." (Examples of teaching for depth rather than breadth are illustrated in Chapter 7.)

As discussed in the first part of this book, knowledge-centered environments also include an emphasis on sense-making—on helping students become metacognitive by expecting new information to make sense and asking for clarification when it doesn't (e.g., Palincsar and Brown, 1984; Schoenfeld, 1983, 1985, 1991). A concern with sense-making raises questions about many existing curricula. For example, it has been argued that many mathematics curricula emphasize

> . . . not so much a form of thinking as a substitute for thinking. The process of calculation or computation only involves the deployment of a set routine with no room for ingenuity or flair, no place for guess work or surprise, no chance for discovery, no need for the human being, in fact (Scheffler, 1975:184).

The argument here is not that students should never learn to compute, but that they should also learn other things about mathematics, especially the fact that it is possible for them to make sense of mathematics and to think mathematically (e.g., Cobb et al., 1992).

There are interesting new approaches to the development of curricula that support learning with understanding and encourage sense making. One is "progressive formalization," which begins with the informal ideas that students bring to school and gradually helps them see how these ideas can be transformed and formalized. Instructional units encourage students to build on their informal ideas in a gradual but structured manner so that they acquire the concepts and procedures of a discipline.

The idea of progressive formalization is exemplified by the algebra strand for middle school students using *Mathematics in Context* (National Center for Research in Mathematical Sciences Education and Freudenthal Institute, 1997). It begins by having students use their own words, pictures, or diagrams to describe mathematical situations to organize their own knowledge and work and to explain their strategies. In later units, students gradually begin to use symbols to describe situations, organize their mathematical work, or express their strategies. At this level, students devise their own symbols or learn some nonconventional notation. Their representations of problem situations and explanations of their work are a mixture of words and symbols. Later, students learn and use standard conventional algebraic notation for writing expressions and equations, for manipulating algebraic expressions and solving equations, and for graphing equations. Movement along this continuum is not necessarily smooth, nor all in one direction.

Although students are actually doing algebra less formally in the earlier grades, they are not forced to generalize their knowledge to a more formal level, nor to operate at a more formal level, before they have had sufficient experience with the underlying concepts. Thus, students may move back and forth among levels of formality depending on the problem situation or on the mathematics involved.

Central to curriculum frameworks such as "progressive formalization" are questions about what is developmentally appropriate to teach at various ages. Such questions represent another example of overlap between learner-centered and knowledge-centered perspectives. Older views that young children are incapable of complex reasoning have been replaced by evidence that children are capable of sophisticated levels of thinking and reasoning when they have the knowledge necessary to support these activities (see Chapter 4). An impressive body of research shows the potential benefit of early access by students to important conceptual ideas. In classrooms using a form of "cognitively guided" instruction in geometry, second-grade children's skills for representing and visualizing three-dimensional forms exceeded those of comparison groups of undergraduate students at a leading university (Lehrer and Chazan, 1998). Young children have also demonstrated powerful forms of early algebraic generalization (Lehrer and Chazan, 1998). Forms of generalization in science, such as experimentation, can be introduced before the secondary school years through a developmental approach to important mathematical and scientific ideas (Schauble et al., 1995; Warren and Rosebery, 1996). Such an approach entails becoming cognizant of the early origins of students' thinking and then identifying how those ideas can be fostered and elaborated (Brown and Campione, 1994).

Attempts to create environments that are knowledge centered also raise important questions about how to foster an integrated understanding of a discipline. Many models of curriculum design seem to produce knowledge and skills that are disconnected rather than organized into coherent wholes. The National Research Council (1990:4) notes that "To the Romans, a curriculum was a rutted course that guided the path of two-wheeled chariots." This rutted path metaphor is an appropriate description of the curriculum for many school subjects:

> Vast numbers of learning objectives, each associated with pedagogical strategies, serve as mile posts along the trail mapped by texts from kindergarten to twelfth grade. . . . Problems are solved not by observing and responding to the natural landscape through which the mathematics curriculum passes, but by mastering time tested routines, conveniently placed along the path (National Research Council, 1990:4).

An alternative to a "rutted path" curriculum is one of "learning the landscape" (Greeno, 1991). In this metaphor, learning is analogous to learning to live in an environment: learning your way around, learning what resources are available, and learning how to use those resources in conducting your activities productively and enjoyably (Greeno, 1991:175). The progressive formalization framework discussed above is consistent with this metaphor. Knowing where one is in a landscape requires a network of connections that link one's present location to the larger space.

Traditional curricula often fail to help students "learn their way around" a discipline. The curricula include the familiar scope and sequence charts that specify procedural objectives to be mastered by students at each grade: though an individual objective might be reasonable, it is not seen as part of a larger network. Yet it is the network, the connections among objectives, that is important. This is the kind of knowledge that characterizes expertise (see Chapter 2). Stress on isolated parts can train students in a series of routines without educating them to understand an overall picture that will ensure the development of integrated knowledge structures and information about conditions of applicability.

An alternative to simply progressing through a series of exercises that derive from a scope and sequence chart is to expose students to the major features of a subject domain as they arise naturally in problem situations. Activities can be structured so that students are able to explore, explain, extend, and evaluate their progress. Ideas are best introduced when students see a need or a reason for their use—this helps them see relevant uses of knowledge to make sense of what they are learning. Problem situations used to engage students may include the historic reasons for the development of the domain, the relationship of that domain to other domains, or the uses of ideas in that domain (see Webb and Romberg, 1992). In Chapter 7 we present examples from history, science, and mathematics instruction that emphasize the importance of introducing ideas and concepts in ways that promote deep understanding.

A challenge for the design of knowledge-centered environments is to strike the appropriate balance between activities designed to promote understanding and those designed to promote the automaticity of skills necessary to function effectively without being overwhelmed by attentional requirements. Students for whom it is effortful to read, write, and calculate can encounter serious difficulties learning. The importance of automaticity has been demonstrated in a number of areas (e.g., Beck et al., 1989, 1991; Hasselbring et al., 1987; LaBerge and Samuels, 1974; see Chapter 2).

ASSESSMENT-CENTERED ENVIRONMENTS

In addition to being learner centered and knowledge centered, effectively designed learning environments must also be assessment centered. The key principles of assessment are that they should provide opportunities for feedback and revision and that what is assessed must be congruent with one's learning goals.

It is important to distinguish between two major uses of assessment. The first, formative assessment, involves the use of assessments (usually administered in the context of the classroom) as sources of feedback to improve teaching and learning. The second, summative assessment, measures what students have learned at the end of some set of learning activities. Examples of formative assessments include teachers' comments on work in progress, such as drafts of papers or preparations for presentations. Examples of summative assessments include teacher-made tests given at the end of a unit of study and state and national achievement tests that students take at the end of a year. Ideally, teachers' formative and summative assessments are aligned with the state and national assessments that students take at the end of the year; often, however, this is not the case. Issues of summative assessment for purposes of national, state, and district accountability are beyond the scope of this volume; our discussion focuses on classroom-based formative and summative assessments.

Formative Assessments and Feedback

Studies of adaptive expertise, learning, transfer, and early development show that feedback is extremely important (see Chapters 2, 3, and 4). Students' thinking must be made visible (through discussions, papers, or tests), and feedback must be provided. Given the goal of learning with understanding, assessments and feedback must focus on understanding, and not only on memory for procedures or facts (although these can be valuable, too). Assessments that emphasize understanding do not necessarily require elaborate or complicated assessment procedures. Even multiple-choice tests can be organized in ways that assess understanding (see below).

Opportunities for feedback should occur continuously, but not intrusively, as a part of instruction. Effective teachers continually attempt to learn about their students' thinking and understanding. They do a great deal of on-line monitoring of both group work and individual performances, and they attempt to assess students' abilities to link their current activities to other parts of the curriculum and their lives. The feedback they give to students can be formal or informal. Effective teachers also help students build skills of self-assessment. Students learn to assess their own work, as well as the work of their peers, in order to help everyone learn more effectively (see, e.g., Vye et al., 1998a, b). Such self-assessment is an important part of the metacognitive approach to instruction (discussed in Chapters 3, 4, and 7).

In many classrooms, opportunities for feedback appear to occur relatively infrequently. Most teacher feedback—grades on tests, papers, worksheets, homework, and on report cards—represent summative assessments that are intended to measure the results of learning. After receiving grades, students typically move on to a new topic and work for another set of grades. Feedback is most valuable when students have the opportunity to use it to revise their thinking as they are working on a unit or project. The addition of opportunities for formative assessment increases students' learning and transfer, and they learn to value opportunities to revise (Barron et al., 1998; Black and William, 1998; Vye et al., 1998b). Opportunities to work collaboratively in groups can also increase the quality of the feedback available to students (Barron, 1991; Bereiter and Scardamalia, 1989; Fuchs et al., 1992; Johnson and Johnson, 1975; Slavin, 1987; Vye et al., 1998a), although many students must be helped to learn how to work collaboratively. New technologies provide opportunities to increase feedback by allowing students, teachers, and content experts to interact both synchronously and asynchronously (see Chapter 9).

A challenge of implementing good assessment practices involves the need to change many teachers', parents', and students' models of what effective learning looks like. Many assessments developed by teachers overly emphasize memory for procedures and facts (Porter et al., 1993). In addition, many standardized tests that are used for accountability still overemphasize memory for isolated facts and procedures, yet teachers are often judged by how well their students do on such tests. One mathematics teacher consistently produced students who scored high on statewide examinations by helping students memorize a number of mathematical procedures (e.g., proofs) that typically appeared on the examinations, but the students did not really understand what they were doing, and often could not answer questions that required an understanding of mathematics (Schoenfeld, 1988).

Appropriately designed assessments can help teachers realize the need to rethink their teaching practices. Many physics teachers have been surprised at their students' inabilities to answer seemingly obvious (to the expert) questions that assessed their students' understanding, and this outcome has motivated them to revise their instructional practices (Redish, 1996). Similarly, visually based assessments of "number sense" (see Case and Moss, 1996) have helped teachers discover the need to help their students develop important aspects of mathematical understanding (Bransford et al., 1998). Innovative assessments that reveal students' understanding of important concepts in science and mathematics have also been developed (Lehrer and Schauble, 1996a, b).

Formats for Assessing Understanding

Teachers have limited time to assess students' performances and provide feedback, but new advances in technology can help solve this problem (see Chapter 9). Even without technology, however, advances have been made in devising simple assessments that measure understanding rather than memorization. In the area of physics, assessments like those used in Chapter 2 to compare experts and novices have been revised for use in classrooms. One task presents students with two problems and asks them to state whether both would be solved using a similar approach and state the reason for the decision:

1. A 2.5-kilogram ball with a radius of 4 centimeters is traveling at 7 meters/second on a rough horizontal surface, but not spinning. At some later time, the ball is rolling without slipping 5 meters/second. How much work was done by friction?
2. A 0.5-kilogram ball with a radius of 15 centimeters is initially sliding at 10 meters/second without spinning. The ball travels on a horizontal surface and eventually rolls without slipping. Find the ball's final velocity.

Novices typically state that these two problems are solved similarly because they match on surface features—both involve a ball sliding and rolling on a horizontal surface. Students who are learning with understanding state that the problems are solved differently: the first can be solved by applying the work-energy theorem; the second can be solved by applying conservation of angular momentum (Hardiman et al., 1989); see Box 6.2. These kinds of assessment items can be used during the course of instruction to monitor the depth of conceptual understanding.

Portfolio assessments are another method of formative assessment. They provide a format for keeping records of students' work as they progress throughout the year and, most importantly, for allowing students to discuss their achievements and difficulties with their teachers, parents, and fellow students (e.g., Wiske, 1997; Wolf, 1988). They take time to implement and they are often implemented poorly—portfolios often become simply another place to store student work but no discussion of the work takes place—but used properly, they provide students and others with valuable information about their learning progress over time.

Theoretical Frameworks for Assessment

A challenge for the learning sciences is to provide a theoretical framework that links assessment practices to learning theory. An important step in this direction is represented by the work of Baxter and Glaser (1997), who

BOX 6.2 How Do You Know?

A 1-kilogram stick that is 2 meters long is placed on a frictionless surface and is free to rotate about a vertical pivot through one end. A 50-gram lump of putty is attached 80 centimeters from the pivot. Which of the following principles would allow you to determine the magnitude of the net force between the stick and the putty when the angular velocity of the system is 3 radians/second?

A. Newton's second law, $\vec{F}_{net} = M\vec{a}$
B. Angular momentum or conservation of angular momentum
C. Linear momentum or conservation of linear momentum
D. Work-energy theorem or conservation of mechanical energy
E. Conservation of linear momentum followed by conservation of mechanical energy

Performance on this item was near random for students finishing an introductory calculus-based physics course. The temptation is to match the "rotation" surface feature of the problem with "angular momentum," when in fact the problem is solved by a simple application of Newton's second law. Data such as these are important for helping teachers guide students toward the development of fluid, transferable knowledge (Leonard et al., 1996).

provide a framework for integrating cognition and context in assessing achievement in science. In their report, performance is described in terms of the content and process task demands of the subject matter and the nature and extent of cognitive activity likely to be observed in a particular assessment situation. The framework provides a basis for examining how developers' intentions are realized in performance assessments that purport to measure reasoning, understanding, and complex problem solving.

Characterizing assessments in terms of components of competence and the content-process demands of the subject matter brings specificity to generic assessment objectives such as "higher level thinking and deep understanding." Characterizing student performance in terms of cognitive activities focuses attention on the differences in competence and subject-matter achievement that can be observed in learning and assessment situations. The kind and quality of cognitive activities in an assessment is a function of the content and process demands of the task involved. For example, consider the content-process framework for science assessment shown in Figure 6.2 (Baxter and Glaser, 1997). In this figure, task demands for content

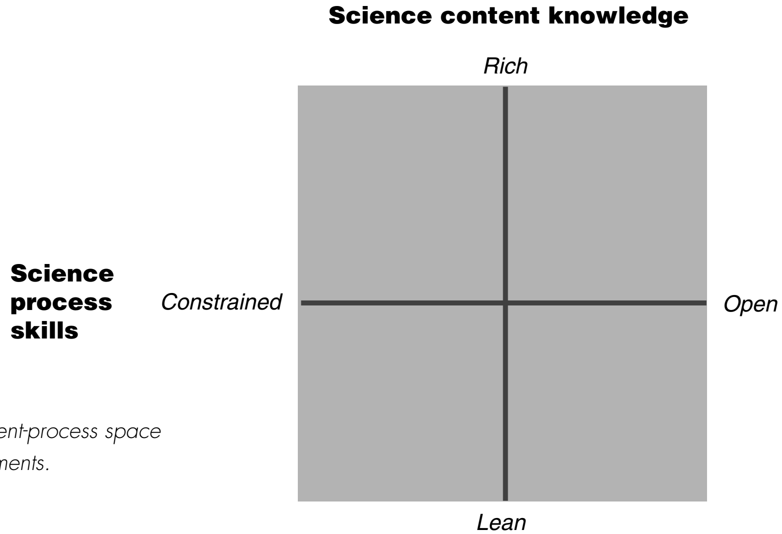


FIGURE 6.2 *Content-process space of science assessments.*

knowledge are conceptualized on a continuum from rich to lean (y axis). At one extreme are knowledge-rich tasks, tasks that require in-depth understanding of subject matter for their completion. At the other extreme are tasks that are not dependent on prior knowledge or related experiences; rather, performance is primarily dependent on the information given in the assessment situation. The task demands for process skills are conceptualized as a continuum from constrained to open (x axis). In open situations, explicit directions are minimized; students are expected to generate and carry out appropriate process skills for problem solution. In process-constrained situations, directions can be of two types: step-by-step, subject-specific procedures given as part of the task, or directions to explain the process skills that are necessary for task completion. In this situation, students are asked to generate explanations, an activity that does not require using the process skills. Assessment tasks can involve many possible combinations of content knowledge and process skills; Table 6.1 illustrates the relationship between the structure of knowledge and the organized cognitive activities.

COMMUNITY-CENTERED ENVIRONMENTS

New developments in the science of learning suggest that the degree to which environments are community centered is also important for learning. Especially important are norms for people learning from one another and continually attempting to improve. We use the term community centered to refer to several aspects of community, including the classroom as a commu-

TABLE 6.1 Cognitive Activity and Structure of Knowledge

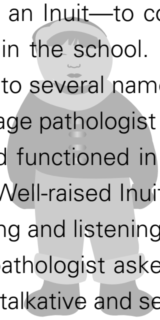
Organized Cognitive Activity	Structure of Knowledge	
	Fragmented	Meaningful
Problem Representation	Surface features and shallow understanding	Underlying principles and relevant concepts
Strategy Use	Undirected trial-and-error problem solving	Efficient, informative, and goal oriented
Self-Monitoring	Minimal and sporadic	Ongoing and flexible
Explanation	Single statement of fact of description of superficial factors	Principled and coherent

nity, the school as a community, and the degree to which students, teachers, and administers feel connected to the larger community of homes, businesses, states, the nation, and even the world.

Classroom and School Communities

At the level of classrooms and schools, learning seems to be enhanced by social norms that value the search for understanding and allow students (and teachers) the freedom to make mistakes in order to learn (e.g., Brown and Campione, 1994; Cobb et al., 1992). Different classrooms and schools reflect different sets of norms and expectations. For example, an unwritten norm that operates in some classrooms is never to get caught making a mistake or not knowing an answer (see, e.g., Holt, 1964). This norm can hinder students' willingness to ask questions when they do not understand the material or to explore new questions and hypotheses. Some norms and expectations are more subject specific. For example, the norms in a mathematics class may be that mathematics is knowing how to compute answers; a much better norm would be that the goal of inquiry is mathematical understanding. Different norms and practices have major effects on what is taught and how it is assessed (e.g., Cobb et al., 1992). Sometimes there are different sets of expectations for different students. Teachers may convey expectations for school success to some students and expectations for school failure to others (MacCorquodale, 1988). For example, girls are sometimes discouraged from participating in higher level mathematics and science. Students, too, may share and convey cultural expectations that proscribe the participation of girls in some classes (Schofield et al., 1990).

BOX 6.3 Talking in Class



A speech-language pathologist working in an Inuit school (in northern Canada) asked a principal—who was not an Inuit—to compile a list of children who had speech and language problems in the school. The list contained a third of the students in the school, and next to several names the principal wrote, "Does not talk in class." The speech-language pathologist consulted a local Inuit teacher for help determining how each child functioned in his or her native language. She looked at the names and said, "Well-raised Inuit children should not talk in class. They should be learning by looking and listening."

When the speech-language pathologist asked that teacher about one toddler she was studying who was very talkative and seemed to the non-Inuit researcher to be very bright, the teacher said: "Do you think he might have a learning problem? Some of these children who don't have such high intelligence have trouble stopping themselves. They don't know when to stop talking" (Crago, 1988:219).

Classroom norms can also encourage modes of participation that may be unfamiliar to some students. For example, some groups rely on learning by observation and listening and then becoming involved in ongoing activities; school-like forms of talking may be unfamiliar for the children whose community has only recently included schools (Rogoff et al., 1993); see Box 6.3.

The sense of community in classrooms is also affected by grading practices, and these can have positive or negative effects depending on the students. For example, Navajo high school students do not treat tests and grades as competitive events the way that Anglo students do (Deyhle and Margonis, 1995). An Anglo high school counselor reported that Navajo parents complained about their children being singled out when the counselor started a "high achiever" bulletin board and wanted to put up the pictures of students with B averages or better. The counselor "compromised" by putting up happy stickers with the students' names on them. A Navajo student, staring at the board, said "The board embarrasses us, to be stuck out like that" (Deyhle and Margonis, 1995:28).

More broadly, competition among students for teacher attention, approval, and grades is a commonly used motivator in U.S. schools. And in some situations, competition may create situations that impede learning. This is especially so if individual competition is at odds with a community ethic of individuals' contributing their strengths to the community (Suina and Smolkin, 1994).

An emphasis on community is also imortant when attempting to borrow successful educational practices from other countries. For example, Japanese teachers spend considerable time working with the whole class, and they frequently ask students who have made errors to share their thinking with the rest of the class. This can be very valuable because it leads to discussions that deepen the understanding of everyone in the class. However, this practice works only because Japanese teachers have developed a classroom culture in which students are skilled at learning from one another and respect the fact that an analysis of errors is fruitful for learning (Hatano and Inagaki, 1996). Japanese students value listening, so they learn from large class discussions even if they do not have many chances to participate. The culture of American classrooms is often very different—many emphasize the importance of being right and contributing by talking. Teaching and learning must be viewed from the perspective of the overall culture of the society and its relationship to the norms of the classrooms. To simply attempt to import one or two Japanese teaching techniques into American classrooms may not produce the desired results.

The sense of community in a school also appears to be strongly affected by the adults who work in that environment. As Barth (1988) states:

> The relationship among adults who live in a school has more to do with the character and quality of the school and with the accomplishments of the students than any other factor.

Studies by Bray (1998) and Talbert and McLaughlin (1993) emphasize the importance of teacher learning communities. We say more about this in Chapter 8.

Connections to the Broader Community

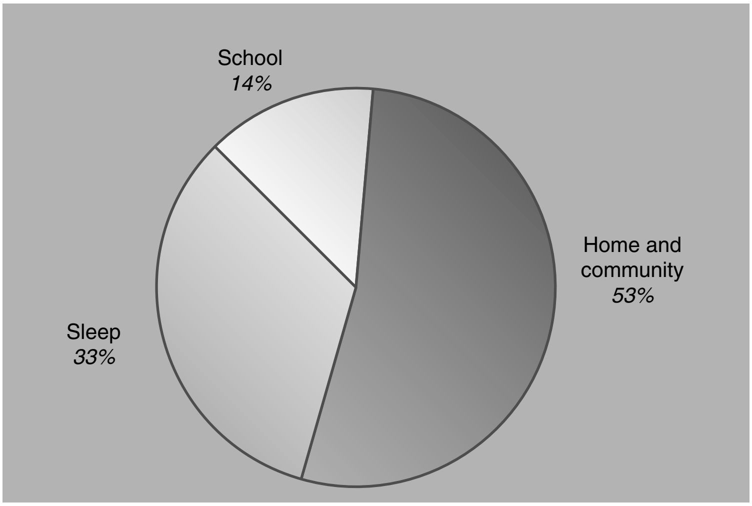
An analysis of learning environments from the perspective of community also includes a concern for connections between the school environment and the broader community, including homes, community centers, after-school programs, and businesses. Chapters 3, 4, and 5 showed that learning takes time; ideally, what is learned in school can be connected to out-of-school learning and vice versa. Often, however, this ideal is not reached. As John Dewey (1916) noted long ago:

> From the standpoint of the child, the great waste in school comes from his inability to utilize the experience he gets outside . . . while on the other hand, he is unable to apply in daily life what he is learning in school. That is the isolation of the school—its isolation from life.

The importance of connecting the school with outside learning activities can be appreciated by considering Figure 6.3, which shows the percentage of time during a typical school year that students spend in school, sleeping, and engaged in other activities (see Bransford et al., 2000). The percentage of time spent in school is comparatively small. If students spend one-third of their nonsleeping time outside of school watching television, this means that they spend more time watching television in a year than they spend in school. (We say more about television and learning in the next section.)

A key environment for learning is the family. Even when family members do not focus consciously on instructional roles, they provide resources for children's learning, activities in which learning occurs, and connections to community (Moll, 1986a, b, 1990). Children also learn from the attitudes of family members toward skills and values of schooling.

The success of the family as a learning environment, especially in children's early years (see Chapter 4), has provided inspiration and guidance for some of the changes recommended in schools. The phenomenal development of children from birth to age 4 or 5 is generally supported by family interactions in which children learn by engaging with and observing others in shared endeavors. Conversations and other interactions that occur around events of interest with trusted and skilled adult and child companions are especially powerful environments for children's learning. Many of the recommendations for changes in schools can be seen as extensions of the learning activities that occur within families. In addition, recommendations



FIGURES 6.3 *Comparison of time spent in school, home and community, and sleep. Percentages were calculated using 180 school days each year, and each school day was estimated to be 6.5 hours in length.*

to include families in classroom activities and planning hold promise of bringing together two powerful systems for supporting children's learning.

Children participate in many other institutions outside their homes that can foster learning. Some of these institutions have learning as part of their goals, including many after-school programs, organizations such as Boy and Girl Scouts and 4-H Clubs, museums, and religious groups. Others make learning more incidental, but learning takes place nevertheless (see McLaughlin, 1990, on youth clubs; Griffin and Cole, 1984, on the Fifth Dimension Program).

Connections to experts outside of school can also have a positive influence on in-school learning because they provide opportunities for students to interact with parents and other people who take an interest in what students are doing. It can be very motivating both to students and teachers to have opportunities to share their work with others. Opportunities to prepare for these events helps teachers raise standards because the consequences go beyond mere scores on a test (e.g., Brown and Campione, 1994, 1996; Cognition and Technology Group at Vanderbilt, in press b).

The idea of outside audiences who present challenges (complete with deadlines) has been incorporated into a number of instructional programs (e.g., Cognition and Technology Group at Vanderbilt, 1997; Wiske, 1997). Working to prepare for outsiders provides motivation that helps teachers maintain student interest. In addition, teachers and students develop a better sense of community as they prepare to face a common challenge. Students are also motivated to prepare for outside audiences who do not come to the classroom but will see their projects. Preparing exhibits for museums represents an excellent example (see Collins et al., 1991). New technologies that enhance the ability to connect classrooms to others in the school, to parents, business leaders, college students, content area experts, and others around the world are discussed in Chapter 9.

TELEVISION

For better or for worse, most children spent a considerable amount of time watching television; it has played an increasingly prominent role in children's development over the past 50 years. Children watch a great deal of television before entering school, and television viewing continues throughout life. In fact, many students spend more hours watching television than attending school. Parents want their children to learn from television; at the same time they are concerned about what they are learning from the programs they watch (Greenfield, 1984).

Watching Different Kinds of Programs

Television programming for children ranges from educational to purely entertaining (see Wright and Huston, 1995). And there are different ways of watching programs—a child may watch in isolation or with an adult. Furthermore, just as in domains like chess, physics, or teaching (see Chapter 2), people's existing knowledge and beliefs affect what they notice, understand, and remember from viewing television (Newcomb and Collins, 1979). The same program can have different effects depending on who is watching and whether the viewing is a solo activity or part of an interactive group. An important distinction is whether the program is intended to be educational or not.

One group of preschoolers aged 2-4 and first-grade students aged 6-7 watched about 7-8 hours of noneducational programming per week; the preschool children also watched an average of 2 hours of educational programming per week, and the older students watched 1 hour. Despite the low ratio of educational to noneducational viewing, the educational programs seemed to have positive benefits. The 2- to 4-year-old preschoolers performed better than non-viewers of educational programs on tests of school readiness, reading, mathematics, and vocabulary as much as 3 years later (Wright and Huston, 1995). Specifically, viewing educational programs was a positive predictor of letter-word knowledge, vocabulary size, and school readiness on standardized achievement tests. For the older students, the viewing of educational programs was related to better performance on tests of reading comprehension and teachers' judgments of school adjustment in first and second grades, compared with children who were infrequent viewers. Overall, the effects of television viewing were not as widespread for the older students, and there were fewer significant effects for the older children than for the preschoolers. It is important to note that the effects of watching educational programs were evident "even when initial language skills, family education, income, and the quality of the home environment are taken into account" (Wright and Huston, 1995:22).

Effects on Beliefs and Attitudes

Television also provides images and role models that can affect how children view themselves, how they see others, attitudes about what academic subjects they should be interested in, and other topics related to person perception. These images can have both positive and negative effects. For example, when 8- to 14-year-olds watched programs designed to show positive attributes of children around the world, they were less likely to say that children from their own country were more interesting or more intelligent (O'Brien, 1981), and they began to see more similarities among people around the world (Greenfield, 1984). And children who watched episodes of Sesame Street featuring handicapped children had more positive feelings toward children with disabilities.

However, children can also misinterpret programs about people from different cultures, depending on what they already know (Newcomb and Collins, 1979). Stereotyping represents a powerful effect of watching television that is potentially negative. Children bring sex role stereotypes with them to school that derive from television programs and commercials (Dorr, 1982).

As a powerful visual medium, television creates stereotypes even when there is no intent to sell an image. But experimental studies indicate that such stereotyping effects decrease with children as young as 5 if adults offer critiques of the stereotypic portrayals as the children watch programs (Dorr, 1982). Thus, entertainment programs can educate in positive ways and learned information can be extended through adult guidance and commentary.

In sum, television has an impact on children's learning that must be taken seriously. But the medium is neither inherently beneficial nor harmful. The content that students watch, and how they watch it, has important effects on what they learn. Especially significant is the fact that informative or educational programming has been shown to have beneficial effects on school achievement and that a preponderance of non-educational, entertainment viewing can have negative effects. Furthermore, the benefits of informative viewing occur despite the fact that the ratio of young children's viewing tends to be 7:1 in favor of entertainment television. These findings support the wisdom of continued attempts to develop and study television programs that can help students acquire the kinds of knowledge, skills, and attitudes that support their learning in school.

THE IMPORTANCE OF ALIGNMENT

In the beginning of this chapter we noted that the four perspectives on learning environments (the degree to which they are learner, knowledge, assessment, and community centered) would be discussed separately but ultimately needed to be aligned in ways that mutually support one another. Alignment is as important for schools as for organizations in general (e.g., Covey, 1990). A key aspect of task analysis (see Chapter 2) is the idea of aligning goals for learning with what is taught, how it is taught, and how it is assessed (both formatively and summatively). Without this alignment, it is difficult to know what is being learned. Students may be learning valuable information, but one cannot tell unless there is alignment between what they are learning and the assessment of that learning. Similarly, students may be learning things that others don't value unless curricula and assessments are aligned with the broad learning goals of communities (Lehrer and Shumow, 1997).

A systems approach to promote coordination among activities is needed to design effective learning environments (Brown and Campione, 1996). Many schools have checklists of innovative practices, such as the use of collaborative learning, teaching for understanding and problem solving, and using formative assessment. Often, however, these activities are not coordinated with one another. Teaching for understanding and problem solving may be "what we do on Fridays"; collaborative learning may be used to promote memorization of fact-based tests; and formative assessments may focus on skills that are totally disconnected from the rest of the students' curriculum. In addition, students may be given opportunities to study collaboratively for tests yet be graded on a curve so that they compete with one another rather than trying to meet particular performance standards. In these situations, activities in the classroom are not aligned.

Activities *within* a particular classroom may be aligned yet fail to fit with the rest of the school. And a school as a whole needs to have a consistent alignment. Some schools communicate a consistent policy about norms and expectations for conduct and achievement. Others send mixed messages. For example, teachers may send behavior problems to the principal, who may inadvertently undermine the teacher by making light of the students' behavior. Similarly, schedules may or may not be made flexible in order to accommodate in-depth inquiry, and schools may or may not be adjusted to minimize disruptions, including nonacademic "pullout" programs and even the number of classroom interruptions made by a principal's overzealous use of the classroom intercom. Overall, different activities within a school may or may not compete with one another and impede overall progress. When principals and teachers work together to define a common vision for their entire school, learning can improve (e.g., Barth, 1988, 1991; Peterson et al., 1995).

Activities within schools must also be aligned with the goals and assessment practices of the community. Ideally, teachers' goals for learning fit with the curriculum they teach and the school's goals, which in turn fit the goals implicit in the tests of accountability used by the school system. Often these factors are out of alignment. Effective change requires a simultaneous consideration of all these factors (e.g., Bransford et al., 1998). The new scientific findings about learning provide a framework for guiding systemic change.

CONCLUSION

The goals and expectations for schooling have changed quite dramatically during the past century, and new goals suggest the need to rethink such questions as what is taught, how it is taught, and how students are assessed. We emphasized that research on learning does not provide a recipe for designing effective learning environments, but it does support the value of asking certain kinds of questions about the design of learning environments.

Four perspectives on the design of learning environments—the degree to which they are student centered, knowledge centered, assessment centered, and community centered—are important in designing these environments.

A focus on the degree to which environments are learner centered is consistent with the strong body of evidence suggesting that learners' use their current knowledge to construct new knowledge and that what they know and believe at the moment affects how they interpret new information. Sometimes learners' current knowledge supports new learning, sometimes it hampers learning: effective instruction begins with what learners bring to the setting; this includes cultural practices and beliefs as well as knowledge of academic content.

Learner-centered environments attempt to help students make connections between their previous knowledge and their current academic tasks. Parents are especially good at helping their children make connections. Teachers have a harder time because they do not share the life experiences of each of their students. Nevertheless, there are ways to systematically become familiar with each student's special interests and strengths.

Effective environments must also be knowledge centered. It is not sufficient only to attempt to teach general problem solving and thinking skills; the ability to think and solve problems requires well-organized knowledge that is accessible in appropriate contexts. An emphasis on being knowledge centered raises a number of questions, such as the degree to which instruction begins with students' current knowledge and skills, rather than simply presents new facts about the subject matter. While young students are capable of grasping more complex concepts than was believed previously, those concepts must be presented in ways that are developmentally appropriate. A knowledge-centered perspective on learning environments also highlights the importance of thinking about designs for curricula. To what extent do they help students learn with understanding versus promote the acquisition of disconnected sets of facts and skills? Curricula that emphasize an excessively broad range of subjects run the risk of developing disconnected rather than connected knowledge; they fit well with the idea of a curriculum as being a well-worn path in a road. An alternative metaphor for curriculum is to help students develop interconnected pathways within a discipline so that they "learn their away around in it" and not lose sight of where they are.

Issues of assessment also represent an important perspective for viewing the design of learning environments. Feedback is fundamental to learning, but opportunities to receive it are often scarce in classrooms. Students may receive grades on tests and essays, but these are summative assessments that occur at the end of projects; also needed are formative assessments that provide students opportunities to revise and hence improve the quality of their thinking and learning. Assessments must reflect the learning goals that define various environments. If the goal is to enhance understanding, it is not sufficient to provide assessments that focus primarily on memory for facts and formulas. Many instructors have changed their approach to teaching after seeing how their students failed to understand seemingly obvious (to the expert) ideas.

The fourth perspective on learning environments involves the degree to which they promote a sense of community. Ideally, students, teachers, and other interested participants share norms that value learning and high standards. Norms such as these increase people's opportunities to interact, receive feedback, and learn. There are several aspects of community, including the community of the classroom, the school, and the connections between the school and the larger community, including the home. The importance of connected communities becomes clear when one examines the relatively small amount of time spent in school compared to other settings. Activities in homes, community centers, and after-school clubs can have important effects on students' academic achievement.

Finally, there needs to be alignment among the four perspectives of learning environments. They all have the potential to overlap and mutually influence one another. Issues of alignment appear to be very important for accelerating learning both within and outside of schools.

7

Effective Teaching: Examples in History, Mathematics, and Science

The preceding chapter explored implications of research on learning for general issues relevant to the design of effective learning environments. We now move to a more detailed exploration of teaching and learning in three disciplines: history, mathematics, and science. We chose these three areas in order to focus on the similarities and differences of disciplines that use different methods of inquiry and analysis. A major goal of our discussion is to explore the knowledge required to teach effectively in a diversity of disciplines.

We noted in Chapter 2 that expertise in particular areas involves more than a set of general problem-solving skills; it also requires well-organized knowledge of concepts and inquiry procedures. Different disciplines are organized differently and have different approaches to inquiry. For example, the evidence needed to support a set of historical claims is different from the evidence needed to prove a mathematical conjecture, and both of these differ from the evidence needed to test a scientific theory. Discussion in Chapter 2 also differentiated between expertise in a discipline and the ability to help others learn about that discipline. To use Shulman's (1987) language, effective teachers need pedagogical content knowledge (knowledge about how to teach in particular disciplines) rather than only knowledge of a particular subject matter.

Pedagogical content knowledge is different from knowledge of general teaching methods. Expert teachers know the structure of their disciplines, and this knowledge provides them with cognitive roadmaps that guide the assignments they give students, the assessments they use to gauge students' progress, and the questions they ask in the give and take of classroom life. In short, their knowledge of the discipline and their knowledge of pedagogy interact. But knowledge of the discipline structure does not in itself guide the teacher. For example, expert teachers are sensitive to those aspects of the discipline that are especially hard or easy for new students to master.

This means that new teachers must develop the ability to "understand in a pedagogically reflective way; they must not only know their own way around a discipline, but must know the 'conceptual barriers' likely to hinder others" (McDonald and Naso, 1986:8). These conceptual barriers differ from discipline to discipline.

An emphasis on interactions between disciplinary knowledge and pedagogical knowledge directly contradicts common misconceptions about what teachers need to know in order to design effective learning environments for their students. The misconceptions are that teaching consists only of a set of general methods, that a good teacher can teach any subject, or that content knowledge alone is sufficient.

Some teachers *are* able to teach in ways that involve a variety of disciplines. However, their ability to do so requires more than a set of general teaching skills. Consider the case of Barb Johnson, who has been a sixth-grade teacher for 12 years at Monroe Middle School. By conventional standards Monroe is a good school. Standardized test scores are about average, class size is small, the building facilities are well maintained, the administrator is a strong instructional leader, and there is little faculty and staff turnover. However, every year parents sending their fifth-grade students from the local elementary schools to Monroe jockey to get their children assigned to Barb Johnson's classes. What happens in her classroom that gives it the reputation of being the best of the best?

During the first week of school Barb Johnson asks her sixth graders two questions: "What questions do you have about yourself?" and "What questions do you have about the world?" The students begin enumerating their questions, "Can they be about silly, little things?" asks one student. "If they're your questions that you really want answered, they're neither silly nor little," replies the teacher. After the students list their individual questions, Barb organizes the students into small groups where they share lists and search for questions they have in common. After much discussion each group comes up with a priority list of questions, rank-ordering the questions about themselves and those about the world.

Back together in a whole group session, Barb Johnson solicits the groups' priorities and works toward consensus for the class's combined lists of questions. These questions become the basis for guiding the curriculum in Barb's class. One question, "Will I live to be 100 years old?" spawned educational investigations into genetics, family and oral history, actuarial science, statistics and probability, heart disease, cancer, and hypertension. The students had the opportunity to seek out information from family members, friends, experts in various fields, on-line computer services, and books, as well as from the teacher. She describes what they had to do as becoming part of a "learning community." According to Barb Johnson, "We decide what are the most compelling intellectual issues, devise ways to investigate those issues and start off on a learning journey. Sometimes we fall short of our goal. Sometimes we reach our goal, but most times we exceed these goals—we learn more than we initially expected" (personal communication).

At the end of an investigation, Barb Johnson works with the students to help them see how their investigations relate to conventional subject-matter areas. They create a chart on which they tally experiences in language and literacy, mathematics, science, social studies and history, music, and art. Students often are surprised at how much and how varied their learning is. Says one student, "I just thought we were having fun. I didn't realize we were learning, too!"

Barb Johnson's teaching is extraordinary. It requires a wide range of disciplinary knowledge because she begins with students' questions rather than with a fixed curriculum. Because of her extensive knowledge, she can map students' questions onto important principles of relevant disciplines. It would not work to simply arm new teachers with general strategies that mirror how she teaches and encourage them to use this approach in their classrooms. Unless they have the relevant disciplinary knowledge, the teachers and the classes would quickly become lost. At the same time, disciplinary knowledge without knowledge about how students learn (i.e., principles consistent with developmental and learning psychology) and how to lead the processes of learning (i.e., pedagogical knowledge) would not yield the kind of learning seen in Barb Johnson's classes (Anderson and Smith, 1987).

In the remainder of this chapter, we present illustrations and discussions of exemplary teaching in history, mathematics, and science. The three examples of history, mathematics, and science are designed to convey a sense of the pedagogical knowledge and content knowledge (Shulman, 1987) that underlie expert teaching. They should help to clarify why effective teaching requires much more than a set of "general teaching skills."

HISTORY

Most people have had quite similar experiences with history courses: they learned the facts and dates that the teacher and the text deemed relevant. This view of history is radically different from the way that historians see their work. Students who think that history is about facts and dates miss exciting opportunities to understand how history is a discipline that is guided by particular rules of evidence and how particular analytical skills can be relevant for understanding events in their lives (see Ravitch and Finn, 1987). Unfortunately, many teachers do not present an exciting approach to history, perhaps because they, too, were taught in the dates-facts method.

Beyond Facts

In Chapter 2, we discussed a study of experts in the field of history and learned that they regard the available evidence as more than lists of facts (Wineburg, 1991). The study contrasted a group of gifted high school seniors with a group of working historians. Both groups were given a test of facts about the American Revolution taken from the chapter review section of a popular United States history textbook. The historians who had backgrounds in American history knew most of the items, while historians whose specialties lay elsewhere knew only a third of the test facts. Several students scored higher than some historians on the factual pretest. In addition to the test of facts, however, the historians and students were presented with a set of historical documents and asked to sort out competing claims and to formulate reasoned interpretations. The historians excelled at this task. Most students, on the other hand, were stymied. Despite the volume of historical information the students possessed, they had little sense of how to use it productively for forming interpretations of events or for reaching conclusions.

Different Views of History by Different Teachers

Different views of history affect how teachers teach history. For example, Wilson and Wineburg (1993) asked two teachers of American history to read a set of student essays on the causes of the American Revolution not as an unbiased or complete and definitive accounts of people and events, but to develop plans for the students' "remediation or enrichment." Teachers were provided with a set of essays on the question, "Evaluate the causes of the American Revolution," written by eleventh-graders for a timed, 45-minute test. Consider the different types of feedback that Mr. Barnes and Ms. Kelsey gave a student paper; see Box 7.1.

Mr. Barnes' comments on the actual content of the essays concentrated on the factual level. Ms. Kelsey's comments addressed broader images of the nature of the domain, without neglecting important errors of fact. Overall, Mr. Barnes saw the papers as an indication of the bell-shaped distribution of abilities; Ms. Kelsey saw them as representing the misconception that history is about memorizing a mass of information and recounting a series of facts. These two teachers had very different ideas about the nature of learning history. Those ideas affected how they taught and what they wanted their students to achieve.

Studies of Outstanding History Teachers

For expert history teachers, their knowledge of the discipline and beliefs about its structure interact with their teaching strategies. Rather than simply introduce students to sets of facts to be learned, these teachers help people to understand the problematic nature of historical interpretation and analysis and to appreciate the relevance of history for their everyday lives.

One example of outstanding history teaching comes form the classroom of Bob Bain, a public school teacher in Beechwood, Ohio. Historians, he notes, are cursed with an abundance of data—the traces of the past threaten to overwhelm them unless they find some way of separating what is important from what is peripheral. The assumptions that historians hold about significance shape how they write their histories, the data they select, and the narrative they compose, as well as the larger schemes they bring to organize and periodize the past. Often these assumptions about historical significance remain unarticulated in the classroom. This contributes to students' beliefs that their textbooks are *the* history rather than *a* history.

Bob Bain begins his ninth-grade high school class by having all the students create a time capsule of what they think are the most important artifacts from the past. The students' task, then, is to put down on paper why they chose the items they did. In this way, the students explicitly articulate their underlying assumptions of what constitutes historical significance. Students' responses are pooled, and he writes them on a large poster that he hangs on the classroom wall. This poster, which Bob Bain calls "Rules for Determining Historical Significance," becomes a lightening rod for class discussions throughout the year, undergoing revisions and elaborations as students become better able to articulate their ideas.

At first, students apply the rules rigidly and algorithmically, with little understanding that just as they made the rules, they can also change them. But as students become more practiced in plying their judgments of significance, they come to see the rules as tools for assaying the arguments of different historians, which allows them to begin to understand why historians disagree. In this instance, the students' growing ability to understand the interpretative nature of history is aided by their teacher's deep understanding of a fundamental principle of the discipline.

Leinhardt and Greeno (1991, 1994) spent 2 years studying a highly accomplished teacher of advanced placement history in an urban high school in Pittsburgh. The teacher, Ms. Sterling, a veteran of over 20 years, began her school year by having her students ponder the meaning of the statement, "Every true history is contemporary history." In the first week of the semester, Sterling thrust her students into the kinds of epistemological issues that one might find in a graduate seminar: "What is history?" "How do we know the past?" "What is the difference between someone who sits down to

BOX 7.1 Comments on Papers on the American Revoloution

Student #7

When the French and Indian war ended, British expected Americans to help them pay back there war debts. That would be a reasonable request if the war was fought for the colonies, but it was fought for English imperialism so you can't blame them for not wanting to pay. The taxes were just the start of the slow turn toward rebellion another factor was when parliament decided to forbid the colonial government to make any more money, Specie became scarcer than ever, and a lot of merchants were pushed into a "two way squeeze" and faced bankruptcy. If I had the choice between being loyal, or rebelling and having something to eat, I know what my choice would be. The colonist who were really loyal never did rebel, and 1/3 support the revolution.

The main thing that turned most people was the amount of propaganda, speeches from people like Patrick Henry, and organizations like the "Association." After the Boston Massacre and the issuing of the Intolerable acts, people were convinced there was a conspiracy in the royal government to extinguish America's liberties. I think a lot of people also just were going with the flow, or were being pressured by the Sons of Liberty. Merchants who didn't go along with boycotts often became the victims of mob violence. Overall though, people were sick of getting overtaxed and walked on and decided let's do something about it.

'write history' and the artifacts that are produced as part of ordinary experience?" The goal of this extended exercise is to help students understand history as an *evidentiary* form of knowledge, not as clusters of fixed names and dates.

One might wonder about the advisability of spending 5 days "defining history" in a curriculum with so much to cover. But it is precisely Sterling's framework of subject-matter knowledge—her overarching understanding of the discipline as a whole—that permits students entry into the advanced world of historical sense-making. By the end of the course, students moved from being passive spectators of the past to enfranchised agents who could participate in the forms of thinking, reasoning, and engagement that are the hallmark of skilled historical cognition. For example, early in the school year, Ms. Sterling asked her students a question about the Constitutional Convention and "what were men able to do." Paul took the question literally: "Uh, I think one of the biggest things that they did, that we talked about yesterday, was the establishment of the first settlements in the Northwest

Mr. Barnes's Summary Comment

—your topic sentence is weak

—more factual detail would improve your essay

—note spelling and grammar corrections

C-

Ms. Kelsey's Summary Comment

—The greatest strength of this essay is its outstanding effort to grapple thoughtfully with the question, why did the colonists rebel? Keep thinking personally, "What if I were here?" It is a great place to start.

—To make the essay *work*, however, you need to refine your organization strategies significantly. Remember that your reader is basically ignorant, so you need to express your view as clearly as you can. Try to form your ideas from the beginning to a middle and then an end.

In the beginning, tell what side you're on: What made the colonists rebel—money, propaganda, conformity?

In the middle, justify your view. What factors support your idea and will convince your reader?

In the end, remind your reader again about your point of view.

Go back and revise and hand this in again!

SOURCE: Wilson and Wineburg (1993:Fig. 1). Reprinted by permission.

area states." But after 2 months of educating students into a way of thinking about history, Paul began to catch on. By January his responses to questions about the fall of the cotton-based economy in the South were linked to British trade policy and colonial ventures in Asia, as well as to the failure of Southern leaders to read public opinion accurately in Great Britain. Ms. Sterling's own understanding of history allowed her to create a classroom in which students not only mastered concepts and facts, but also used them in authentic ways to craft historical explanations.

Debating the Evidence

Elizabeth Jensen prepares her group of eleventh graders to debate the following resolution:

> Resolved: The British government possesses the legitimate authority to tax the American colonies.

As her students enter the classroom they arrange their desks into three groups—on the left of the room a group of "rebels," on the right, a group of "loyalists," and in the front, a group of "judges." Off to the side with a spiral notebook on her lap sits Jensen, a short woman in her late 30s with a booming voice. But today that voice is silent as her students take up the question of the legitimacy of British taxation in the American colonies.

The rebels' first speaker, a 16-year-old girl with a Grateful Dead T-shirt and one dangling earring, takes a paper from her notebook and begins:

> England says she keeps troops here for our own protection. On face value, this seems reasonable enough, but there is really no substance to their claims. First of all, who do they think they are protecting us from? The French? Quoting from our friend Mr. Bailey on page 54, 'By the settlement in Paris in 1763, French power was thrown completely off the continent of North America.' Clearly not the French then. Maybe they need to protect us from the Spanish? Yet the same war also subdued the Spanish, so they are no real worry either. In fact, the only threat to our order is the Indians . . . but . . . we have a decent militia of our own. . . . So why are they putting troops here? The only possible reason is to keep us in line. With more and more troops coming over, soon every freedom we hold dear will be stripped away. The great irony is that Britain expects us to pay for these vicious troops, these British squelchers of colonial justice.

A loyalist responds:

> We moved here, we are paying less taxes than we did for two generations in England, and you complain? Let's look at why we are being taxed—the main reason is probably because England has a debt of £140,000,000. . . . This sounds a little greedy, I mean what right do they have to take our money simply because they have the power over us. But did you know that over one-half of their war debt was caused by defending us in the French and Indian War. . . . Taxation without representation isn't fair. Indeed, it's tyranny. Yet virtual representation makes this whining of yours an untruth. Every British citizen, whether he had a right to vote or not, is represented in Parliament. Why does this representation not extend to America?

A rebel questions the loyalist about this:

> Rebel: What benefits do we get out of paying taxes to the crown?
>
> Loyalist: We benefit from the protection.
>
> Rebel: (cutting in) Is that the only benefit you claim, protection?
>
> Loyalist: Yes—and all the rights of an Englishman.
>
> Rebel: Okay, then what about the Intolerable Acts . . . denying us rights of British subjects. What about the rights we are denied?
>
> Loyalist: The Sons of Liberty tarred and feather people, pillaged homes—they were definitely deserving of some sort of punishment.
>
> Rebel: So should all the colonies be punished for the acts of a few colonies?

For a moment, the room is a cacophony of charges and countercharges. "It's the same as in Birmingham," shouts a loyalist. A rebel snorts disparagingly, "Virtual representation is bull." Thirty-two students seem to be talking at once, while the presiding judge, a wiry student with horn-rimmed glasses, bangs his gavel to no avail. The teacher, still in the corner, still with spiral notebook in lap, issues her only command of the day. "Hold still!" she thunders. Order is restored and the loyalists continue their opening argument (from Wineburg and Wilson, 1991).

Another example of Elizabeth Jensen's teaching involves her efforts to help her high school students understand the debates between Federalists and anti-Federalists. She knows that her 15- and 16-year-olds cannot begin to grasp the complexities of the debates without first understanding that these disagreements were rooted in fundamentally different conceptions of human nature—a point glossed over in two paragraphs in her history textbook. Rather than beginning the year with a unit on European discovery and exploration, as her text dictates, she begins with a conference on the nature of man. Students in her eleventh-grade history class read excerpts from the writings of philosophers (Hume, Locke, Plato, and Aristotle), leaders of state and revolutionaries (Jefferson, Lenin, Gandhi), and tyrants (Hitler, Mussolini), presenting and advocating these views before their classmates. Six weeks later, when it is time to study the ratification of the Constitution, these now-familiar figures—Plato, Aristotle, and others—are reconvened to be courted by impassioned groups of Federalists and anti-Federalists. It is Elizabeth Jensen's understanding of what she wants to teach and what adolescents already know that allows her to craft an activity that helps students get a feel for the domain that awaits them: decisions about rebellion, the Constitution, federalism, slavery, and the nature of a government.

Conclusion

These examples provide glimpses of outstanding teaching in the discipline of history. The examples do not come from "gifted teachers" who know how to teach anything: they demonstrate, instead, that expert teachers have a deep understanding of the structure and epistemologies of their disciplines, combined with knowledge of the kinds of teaching activities that will help students come to understand the discipline for themselves. As we previously noted, this point sharply contradicts one of the popular—and dangerous—myths about teaching: teaching is a generic skill and a good teacher can teach any subject. Numerous studies demonstrate that any curriculum—including a textbook—is mediated by a teacher's understanding of the subject domain (for history, see Wineburg and Wilson, 1988; for math, see Ball, 1993; for English, see Grossman et al., 1989). The uniqueness of the content knowledge and pedagogical knowledge necessary to teach history becomes clearer as one explores outstanding teaching in other disciplines.

MATHEMATICS

As is the case in history, most people believe that they know what mathematics is about—computation. Most people are familiar with only the computational aspects of mathematics and so are likely to argue for its place in the school curriculum and for traditional methods of instructing children in computation. In contrast, mathematicians see computation as merely a tool in the real stuff of mathematics, which includes problem solving, and characterizing and understanding structure and patterns. The current debate concerning what students should learn in mathematics seems to set proponents of teaching computational skills against the advocates of fostering conceptual understanding and reflects the wide range of beliefs about what aspects of mathematics are important to know. A growing body of research provides convincing evidence that what teachers know and believe about mathematics is closely linked to their instructional decisions and actions (Brown, 1985; National Council of Teachers of Mathematics, 1989; Wilson, 1990a, b; Brophy, 1990; Thompson, 1992).

Teachers' ideas about mathematics, mathematics teaching, and mathematics learning directly influence their notions about what to teach and how to teach it—an interdependence of beliefs and knowledge about pedagogy and subject matter (e.g., Gamoran, 1994; Stein et al., 1990). It shows that teachers' goals for instruction are, to a large extent, a reflection of what they think is important in mathematics and how they think students best learn it. Thus, as we examine mathematics instruction, we need to pay attention to the subject-matter knowledge of teachers, their pedagogical knowledge (general and content specific), and their knowledge of children as learners of mathematics. Paying attention to these domains of knowledge also leads us to examine teachers' goals for instruction.

If students in mathematics classes are to learn mathematics with understanding—a goal that is accepted by almost everyone in the current debate over the role of computational skills in mathematics classrooms—then it is important to examine examples of teaching for understanding and to analyze the roles of the teacher and the knowledge that underlies the teacher's enactments of those roles. In this section, we examine three cases of mathematics instruction that are viewed as being close to the current vision of exemplary instruction and discuss the knowledge base on which the teacher is drawing, as well as the beliefs and goals which guide his or her instructional decisions.

Multiplication with Meaning

For teaching multidigit multiplication, teacher-researcher Magdelene Lampert created a series of lessons in which she taught a heterogeneous group of 28 fourth-grade students. The students ranged in computational skill from beginning to learn the single-digit multiplication facts to being able to accurately solve n-digit by n-digit multiplications. The lessons were intended to give children experiences in which the important mathematical principles of additive and multiplicative composition, associativity, commutativity, and the distributive property of multiplication over addition were all evident in the steps of the procedures used to arrive at an answer (Lampert, 1986:316). It is clear from her description of her instruction that both her deep understanding of multiplicative structures and her knowledge of a wide range of representations and problem situations related to multiplication were brought to bear as she planned and taught these lessons. It is also clear that her goals for the lessons included not only those related to students' understanding of mathematics, but also those related to students' development as independent, thoughtful problem solvers. Lampert (1986:339) described her role as follows:

> My role was to bring students' ideas about how to solve or analyze problems into the public forum of the classroom, to referee arguments about whether those ideas were reasonable, and to sanction students' intuitive use of mathematical principles as legitimate. I also taught new information in the form of symbolic structures and emphasized the connection between symbols and operations on quantities, but I made it a classroom requirement that students use their own ways of deciding whether something was mathematically reasonable in doing the work. If one conceives of the teacher's role in this way, it is difficult to separate instruction in mathematics content from building a culture of sense-making in the classroom, wherein teacher and students have a view of themselves as responsible for ascertaining the legitimacy of procedures by reference to known mathematical principles. On the part of the teacher, the principles might be known as a more formal abstract system, whereas on the part of the learners, they are known in relation to familiar experiential contexts. But what seems most important is that teachers and students together are disposed toward a particular way of viewing and doing mathematics in the classroom.

Magdelene Lampert set out to connect what students already knew about multidigit multiplication with principled conceptual knowledge. She did so in three sets of lessons. The first set used coin problems, such as "Using only two kinds of coins, make $1.00 using 19 coins," which encouraged children to draw on their familiarity with coins and mathematical principles that coin trading requires. Another set of lessons used simple stories and drawings to illustrate the ways in which large quantities could be grouped for easier counting. Finally, the third set of lessons used only numbers and arithmetic symbols to represent problems. Throughout the lessons, students were challenged to explain their answers and to rely on their arguments, rather than to rely on the teacher or book for verification of correctness. An example serves to highlight this approach; see Box 7.2.

Lampert (1986:337) concludes:

> . . . students used principled knowledge that was tied to the language of groups to explain what they were seeing. They were able to talk meaningfully about place value and order of operations to give legitimacy to procedures and to reason about their outcomes, even though they did not use technical terms to do so. I took their experimentations and arguments as evidence that they had come to see mathematics as more than a set of procedures for finding answers.

Clearly, her own deep understanding of mathematics comes into play as she teaches these lessons. It is worth noting that her goal of helping students see what is mathematically legitimate shapes the way in which she designs lessons to develop students' understanding of two-digit multiplication.

Understanding Negative Numbers

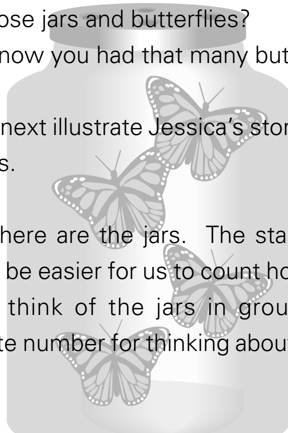
Helping third-grade students extend their understanding of numbers from the natural numbers to the integers is a challenge undertaken by another teacher-researcher. Deborah Ball's work provides another snapshot of teaching that draws on extensive subject content and pedagogical content knowledge. Her goals in instruction include "developing a practice that respects the integrity both of mathematics as a discipline *and* of children as mathematical thinkers" (Ball, 1993). That is, she not only takes into account what the important mathematical ideas are, but also how children think about the particular area of mathematics on which she is focusing. She draws on both her understanding of the integers as mathematical entities (subject-matter knowledge) and her extensive pedagogical content knowledge specifically about integers. Like Lampert, Ball's goals go beyond the boundaries of what is typically considered mathematics and include developing a culture in which students conjecture, experiment, build arguments, and frame and solve problems—the work of mathematicians.

Deborah Ball's description of work highlights the importance and difficulty of figuring out powerful and effective ways to represent key mathematical ideas to children (see Ball, 1993). A wealth of possible models for negative numbers exists and she reviewed a number of them—magic peanuts, money, game scoring, a frog on a number line, buildings with floors above and below ground. She decided to use the building model first and money later: she was acutely aware of the strengths and limitations of each

BOX 7.2 How Many Altogether?

The teacher begins with a request for an example of a basic computation.

> Teacher: Can anyone give me a story that could go with this multiplication . . .12 × 4?
>
> Jessica: There were 12 jars, and each had 4 butterflies in it.
>
> Teacher: And if I did this multiplication and found the answer, what would I know about those jars and butterflies?
>
> Jessica: You'd know you had that many butterflies altogether.



The teacher and students next illustrate Jessica's story and construct a procedure for counting the butterflies.

> Teacher: Okay, here are the jars. The stars in them will stand for butterflies. Now, it will be easier for us to count how many butterflies there are altogether, if we think of the jars in groups. And as usual, the mathematician's favorite number for thinking about groups is? [Draw a loop around 10 jars.]
>
> Sally: 10.

The lesson progresses as the teacher and students construct a pictorial representation of grouping 10 sets of four butterflies and having 2 jars not in the group; they recognize that 12 × 4 can be thought of as 10 × 4 plus 2 × 4. Lampert then has the children explore other ways of grouping the jars, for example, into two groups of 6 jars.

The students are obviously surprised that 6 × 4 plus 6 × 4 produces the same number as 10 × 4 plus 2 × 4. For Lampert, this is important information about the students' understanding (formative assessment—see Chapter 6). It is a sign that she needs to do many more activities involving different groupings. In subsequent lessons, students are challenged with problems in which the two-digit number in the multiplication is much bigger and, ultimately, in which both numbers are quite large—28 × 65. Students continue to develop their understanding of the principles that govern multiplication and to invent computational procedures based on those principles. Students defend the reasonableness of their procedures by using drawings and stories. Eventually, students explore more traditional as well as alternative algorithms for two-digit multiplication, using only written symbols.

model as a way for representing the key properties of numbers, particularly those of magnitude and direction. Reading Deborah Ball's description of her deliberations, one is struck by the complexity of selecting appropriate models for particular mathematical ideas and processes. She hoped that the positional aspects of the building model would help children recognize that negative numbers were not equivalent to zero, a common misconception. She was aware that the building model would be difficult to use for modeling subtraction of negative numbers.

Deborah Ball begins her work with the students, using the building model by labeling its floors. Students readily labeled the underground floors and accepted them as "below zero." They then explored what happened as little paper people entered an elevator at some floor and rode to another floor. This was used to introduce the conventions of writing addition and subtraction problems involving integers $4 - 6 = -2$ and $-2 + 5 = 3$. Students were presented with increasingly difficult problems. For example, "How many ways are there for a person to get to the second floor?" Working with the building model allowed students to generate a number of observations. For example, one student noticed that "any number below zero plus that same number above zero equals zero" (Ball, 1993:381). However, the model failed to allow for explorations for such problems $5 + (-6)$ and Ball was concerned that students were not developing a sense that –5 was less than –2—it was lower, but not necessarily less. Ball then used a model of money as a second representational context for exploring negative numbers, noting that it, too, has limitations.

Clearly, Deborah Ball's knowledge of the possible representations of integers (pedagogical content knowledge) and her understanding of the important mathematical properties of integers were foundational to her planning and her instruction. Again, her goals related to developing students' mathematical authority, and a sense of community also came into play. Like Lampert, Ball wanted her students to accept the responsibility of deciding when a solution is reasonable and likely to be correct, rather than depending on text or teacher for confirmation of correctness.

Guided Discussion

The work of Lampert and Ball highlights the role of a teacher's knowledge of content and pedagogical content knowledge in planning and teaching mathematics lessons. It also suggests the importance of the teacher's understanding of children as learners. The concept of cognitively guided instruction helps illustrate another important characteristic of effective mathematics instruction: that teachers not only need knowledge of a particular topic within mathematics and knowledge of how learners think about the particular topic, but also need to develop knowledge about how the individual children in their classrooms think about the topic (Carpenter and Fennema, 1992; Carpenter et al., 1996; Fennema et al., 1996). Teachers, it is claimed, will use their knowledge to make appropriate instructional decisions to assist students to construct their mathematical knowledge. In this approach, the idea of domains of knowledge for teaching (Shulman, 1986) is extended to include teachers' knowledge of individual learners in their classrooms.

Cognitively guided instruction is used by Annie Keith, who teaches a combination first- and second-grade class in an elementary school in Madison Wisconsin (Hiebert et al., 1997). Her instructional practices are an example of what is possible when a teacher understands children's thinking and uses that understanding to guide her teaching. A portrait of Ms. Keith's classroom reveals also how her knowledge of mathematics and pedagogy influence her instructional decisions.

Word problems form the basis for almost all instruction in Annie Keith's classroom. Students spend a great deal of time discussing alternative strategies with each other, in groups, and as a whole class. The teacher often participates in these discussions but almost never demonstrates the solution to problems. Important ideas in mathematics are developed as students explore solutions to problems, rather than being a focus of instruction per se. For example, place-value concepts are developed as students use base-10 materials, such as base-10 blocks and counting frames, to solve word problems involving multidigit numbers.

Mathematics instruction in Annie Keith's class takes place in a number of different settings. Everyday first-grade and second-grade activities, such as sharing snacks, lunch count, and attendance, regularly serve as contexts for problem-solving tasks. Mathematics lessons frequently make use of math centers in which the students do a variety of activities. On any given day, children at one center may solve word problems presented by the teacher while at another center children write word problems to present to the class later or play a math game.

She continually challenges her students to think and to try to make sense of what they are doing in math. She uses the activities as opportunities for her to learn what individual students know and understand about mathematics. As students work in groups to solve problems, she observes the various solutions and mentally makes notes about which students should present their work: she wants a variety of solutions presented so that students will have an opportunity to learn from each other. Her knowledge of the important ideas in mathematics serves as one framework for the selection process, but her understanding of how children think about the mathematical ideas they are using also affects her decisions about who should present. She might select a solution that is actually incorrect to be presented so that she can initiate a discussion of a common misconception. Or she may select a solution that is more sophisticated than most students have used in order to provide an opportunity for students to see the benefits of such a strategy. Both the presentations of solutions and the class discussions that follow provide her with information about what her students know and what problems she should use with them next.

Annie Keith's strong belief that children need to construct their understanding of mathematical ideas by building on what they already know guides her instructional decisions. She forms hypotheses about what her students understand and selects instructional activities based on these hypotheses. She modifies her instruction as she gathers additional information about her students and compares it with the mathematics she wants them to learn. Her instructional decisions give her clear diagnoses of individual students' current state of understanding. Her approach is not a free-for-all without teacher guidance: rather, it is instruction that builds on students' understandings and is carefully orchestrated by the teacher, who is aware of what is mathematically important and also what is important to the learner's progress.

Model-Based Reasoning

Some attempts to revitalize mathematics instruction have emphasized the importance of modeling phenomena. Work on modeling can be done from kindergarten through twelfth grade (K-12). Modeling involves cycles of model construction, model evaluation, and model revision. It is central to professional practice in many disciplines, such as mathematics and science, but it is largely missing from school instruction. Modeling practices are ubiquitous and diverse, ranging from the construction of physical models, such as a planetarium or a model of the human vascular system, to the development of abstract symbol systems, exemplified by the mathematics of algebra, geometry, and calculus. The ubiquity and diversity of models in these disciplines suggest that modeling can help students develop understanding about a wide range of important ideas. Modeling practices can and should be fostered at every age and grade level (Clement, 1989; Hestenes, 1992; Lehrer and Romberg, 1996a, b; Schauble et al., 1995; see Box 7.3).

Taking a model-based approach to a problem entails inventing (or selecting) a model, exploring the qualities of the model, and then applying the model to answer a question of interest. For example, the geometry of triangles has an internal logic and also has predictive power for phenomena ranging from optics to wayfinding (as in navigational systems) to laying floor tile. Modeling emphasizes a need for forms of mathematics that are typically underrepresented in the standard curriculum, such as spatial visualization and geometry, data structure, measurement, and uncertainty. For example, the scientific study of animal behavior, like bird foraging, is severely limited unless one also has access to such mathematical concepts as variability and uncertainty. Hence, the practice of modeling introduces the further explorations of important "big ideas" in disciplines.

Conclusion

Increasingly, approaches to early mathematics teaching incorporate the premises that all learning involves extending understanding to new situations, that young children come to school with many ideas about mathematics, that knowledge relevant to a new setting is not always accessed spontaneously, and that learning can be enhanced by respecting and encouraging children to try out the ideas and strategies that they bring to school-based learning in classrooms. Rather than beginning mathematics instruction by focusing solely on computational algorithms, such as addition and subtraction, students are encouraged to invent their own strategies for solving problems and to discuss why those strategies work. Teachers may also explicitly prompt students to think about aspects of their everyday life that are potentially relevant for further learning. For example, everyday experiences of walking and related ideas about position and direction can serve as a springboard for developing corresponding mathematics about the structure of large-scale space, position, and direction (Lehrer and Romberg, 1996b).

As research continues to provide good examples of instruction that help children learn important mathematics, there will be better understanding of the roles that teachers' knowledge, beliefs, and goals play in their instructional thinking and actions. The examples we have provided here make it clear that the selection of tasks and the guidance of students' thinking as they work through tasks is highly dependent on teachers' knowledge of mathematics, pedagogical content knowledge, and knowledge of students in general.

SCIENCE

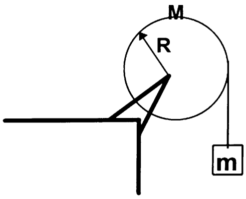
Two recent examples in physics illustrate how research findings can be used to design instructional strategies that promote the sort of problem-solving behavior observed in experts. Undergraduates who had finished an introductory physics course were asked to spend a total of 10 hours, spread over several weeks, solving physics problems using a computer-based tool that constrained them to perform a conceptual analysis of the problems based on a hierarchy of principles and procedures that could be applied to solve them (Dufresne et al., 1996). This approach was motivated by research on expertise (discussed in Chapter 2). The reader will recall that, when asked to state an approach to solving a problem, physicists generally discuss principles and procedures. Novices, in contrast, tend to discuss

BOX 7.3 Qualitative Strategies Written by Students

Students enrolled in an introductory physics course were asked to write a strategy for an exam problem

Exam Problem:

A disk of mass, M = 2 kg, and radius, R = 0.4 m, has string wound around it and is free to rotate about an axle through its center. A block of mass, M = 1 kg, is attached to the end of the string, and the system is released from rest with no slack in the string. What is the speed of the block after it has fallen a distance, d = 0.5 m. Don't forget to provide both a strategy and a solution.



Strategy 1: Use the conservation of energy since the only nonconservative force in the system is the tension in the rope attached to the mass M and wound around the disk (assuming there is no friction between the axle and the disk, and the mass M and the air), and the work done by the tension to the disk and the mass cancel each other out. First, set up a coordinate system so the potential energy of the system at the start can be determined. There will be no kinetic energy at the start since it starts at rest. Therefore the potential energy is all the initial energy. Now set the initial energy equal to the final energy that is made up of the kinetic energy of the disk plus the mass M and any potential energy left in the system with respect to the chosen coordinate system.

Strategy 2: I would use conservation of mechanical energy to solve this problem. The mass M has some potential energy while it is hanging there. When the block starts to accelerate downward the potential energy is transformed into rotational kinetic energy

specific equations that could be used to manipulate variables given in the problem (Chi et al., 1981). When compared with a group of students who solved the same problems on their own, the students who used the computer to carry out the hierarchical analyses performed noticeably better in subsequent measures of expertise. For example, in problem solving, those who performed the hierarchical analyses outperformed those who did not, whether measured in terms of overall problem-solving performance, ability to arrive at the correct answer, or ability to apply appropriate principles to solve the problems; see Figure 7.1. Furthermore, similar differences emerged in problem categorization: students who performed the hierarchical analyses considered principles (as opposed to surface features) more often in of the disk and kinetic energy of the falling mass. Equating the initial and final states and using the relationship between v and ω the speed of M can be found. Mechanical energy is conserved even with the nonconservative tension force because the tension force is internal to the system (pulley, mass, rope).

Strategy 3: In trying to find the speed of the block I would try to find angular momentum kinetic energy, use gravity. I would also use rotational kinematics and moment of inertia around the center of mass for the disk.

Strategy 4: There will be a torque about the center of mass due to the weight of the block, M. The force pulling downward is mg. The moment of inertia about the axle is 1/2 MR^2. The moment of inertia multiplied by the angular acceleration. By plugging these values into a kinematic expression, the angular speed can be calculated. Then, the angular speed times the radius gives you the velocity of the block.

The first two strategies display an excellent understanding of the principles, justification, and procedures that could be used to solve the problem (the what, why, and how for solving the problem). The last two strategies are largely a shopping list of physics terms or equations that were covered in the course, but the students are not able to articulate why or how they apply to the problem under consideration.

Having students write strategies (after modeling strategy writing for them and providing suitable scaffolding to ensure progress) provides an excellent formative assessment tool for monitoring whether or not students are making the appropriate links between problem contexts, and the principles and procedures that could be applied to solve them (see Leonard et al., 1996).

deciding whether or not two problems would be solved similarly; see Figure 7.2. (See Chapter 6 for an example of the type of item used in the categorization task of Figure 7.2.) It is also worth noting that both Figures 7.1 and 7.2 illustrate two other issues that we have discussed in this volume, namely that time on task is a major indicator for learning and that deliberate practice is an efficient way to promote expertise. In both cases, the control group made significant improvements simply as a result of practice (time on task), but the experimental group showed more improvements for the same amount of training time (deliberate practice).

Introductory physics courses have also been taught successfully with an approach for problem solving that begins with a qualitative hierarchical analy-

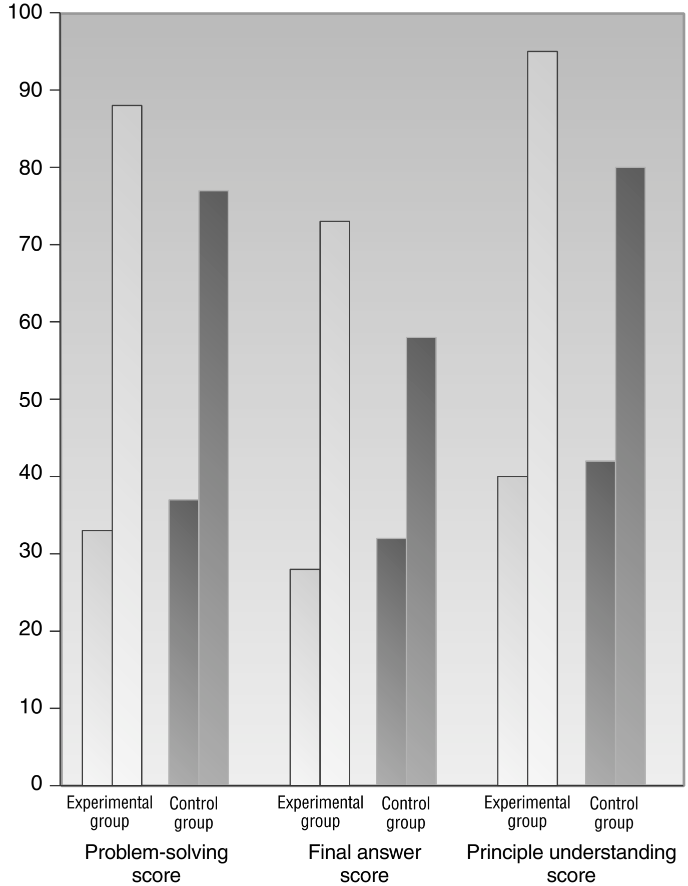


FIGURE 7.1 *Effects of two methods of training on problem-solving, final answer, and principle understanding. SOURCE: Dufresne et al. (1992).*

sis of the problems (Leonard et al., 1996). Undergraduate engineering students were instructed to write qualitative strategies for solving problems before attempting to solve them (based on Chi et al., 1981). The strategies consisted of a coherent verbal description of how a problem could be solved and contained three components: the major principle to be applied; the justification for why the principle was applicable; and the procedures for applying the principle. That is, the what, why, and how of solving the problem were explicitly delineated; see Box 7.4. Compared with students who took a traditional course, students in the strategy-based course per-

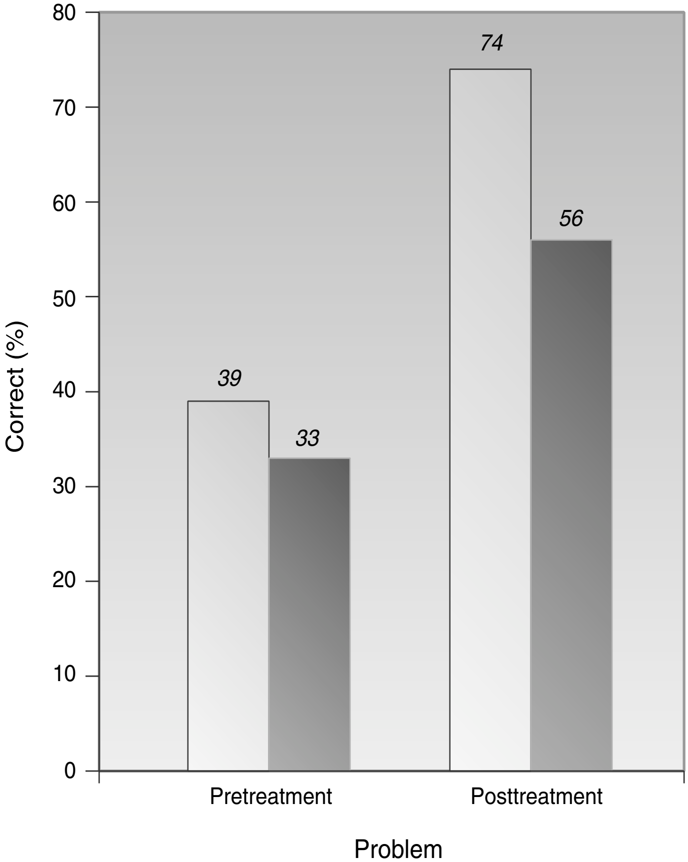


FIGURE 7.2 *Effects of two methods of training on considering principles for categorizing problems. SOURCE: Dufresne et al. (1992).*

formed significantly better in their ability to categorize problems according to the relevant principles that could be applied to solve them; see Figure 7.3.

Hierarchical structures are useful strategies for helping novices both recall knowledge and solve problems. For example, physics novices who had completed and received good grades in an introductory college physics course were trained to generate a problem analysis called a theoretical problem description (Heller and Reif, 1984). The analysis consists of describing force problems in terms of concepts, principles, and heuristics. With such an approach, novices substantially improved in their ability to solve problems, even though the type of theoretical problem description used in the study

BOX 7.4 Which Water Tastes Better?

The seventh- and eighth-grade students in a Haitian Creole bilingual program wanted to find the "truth" of a belief held by most of their classmates: that drinking water from the fountain on the third floor, where the junior high was located, was superior to the water from the other fountains in their school. Challenged by their teacher, the students set out to determine whether they actually preferred the water from the third floor or only thought they did.

As a first step, the students designed and took a blind taste test of the water from fountains on all three floors of the building. They found, to their surprise, that two-thirds of them chose the water from the first-floor fountain, even though they all said that they preferred drinking from the third-floor fountain. The students did not believe the data. They held firmly to their beliefs that the first-floor fountain was the worst because "all the little kids slobber in it." (The first-floor fountain is located near the kindergarten and first-grade classrooms.) Their teacher was also suspicious of the results because she had expected no differences among the three water fountains. These beliefs and suspicions motivated the students to conduct a second taste test with a larger sample drawn from the rest of the junior high.

The students decided where, when, and how to run their experiment. They discussed methodological issues: How to collect the water, how to hide the identity of the sources, and, crucially, how many fountains to include. They decided to include the same three fountains as before so that they could compare results.

was not a natural one for novices. Novices untrained in the theoretical descriptions were generally unable to generate appropriate descriptions on their own—even given fairly routine problems. Skills, such as the ability to describe a problem in detail before attempting a solution, the ability to determine what relevant information should enter the analysis of a problem, and the ability to decide which procedures can be used to generate problem descriptions and analyses, are tacitly used by experts but rarely taught explicitly in physics courses.

Another approach helps students organize knowledge by imposing a hierarchical organization on the performance of different tasks in physics (Eylon and Reif, 1984). Students who received a particular physics argument that was organized in hierarchical form performed various recall and problem-solving tasks better than subjects who received the same argument non-hierarchically. Similarly, students who received a hierarchical organization of problem-solving strategies performed much better than subjects who received the same strategies organized non-hierarchically. Thus, helping

They worried about bias in the voting process: What if some students voted more than once? Each student in the class volunteered to organize a piece of the experiment. About 40 students participated in the blind taste test. When they analyzed their data, they found support for their earlier results: 88 percent of the junior high students *thought* they preferred water from the third-floor fountain, but 55 percent actually chose the water from the first floor (a result of 33 percent would be chance).

Faced with this evidence, the students' suspicions turned to curiosity. Why was the water from the first-floor fountain preferred? How can they determine the source of the preference? They decided to analyze the school's water along several dimensions, among them acidity, salinity, temperature, and bacteria. They found that all the fountains had unacceptably high levels of bacteria. In fact, the first-floor fountain (the one most preferred) had the highest bacterial count. They also found that the water from the first-floor fountain was 20 degrees (Fahrenheit) colder than the water from fountains on the other floors. Based on their findings, they concluded that temperature was probably a deciding factor in taste preference. They hypothesized that the water was naturally cooled as it sat in the city's underground pipes during the winter months (the study was conducted in February) and warmed as it flowed from the basement to the third floor.

SOURCE: Rosebery et al. (1992).

students to organize their knowledge is as important as the knowledge itself, since knowledge organization is likely to affect students' intellectual performance.

These examples demonstrate the importance of deliberate practice and of having a "coach" who provides feedback for ways of optimizing performance (see Chapter 3). If students had simply been given problems to solve on their own (an instructional practice used in all the sciences), it is highly unlikely that they would have spent time efficiently. Students might get stuck for minutes, or even hours, in attempting a solution to a problem and either give up or waste lots of time. In Chapter 3, we discussed ways in which learners profit from errors and that making mistakes is not always time wasted. However, it is not efficient if a student spends most of the problem-solving time rehearsing procedures that are not optimal for promoting skilled performance, such as finding and manipulating equations to solve the problem, rather than identifying the underlying principle and procedures that apply to the problem and then constructing the specific equa-

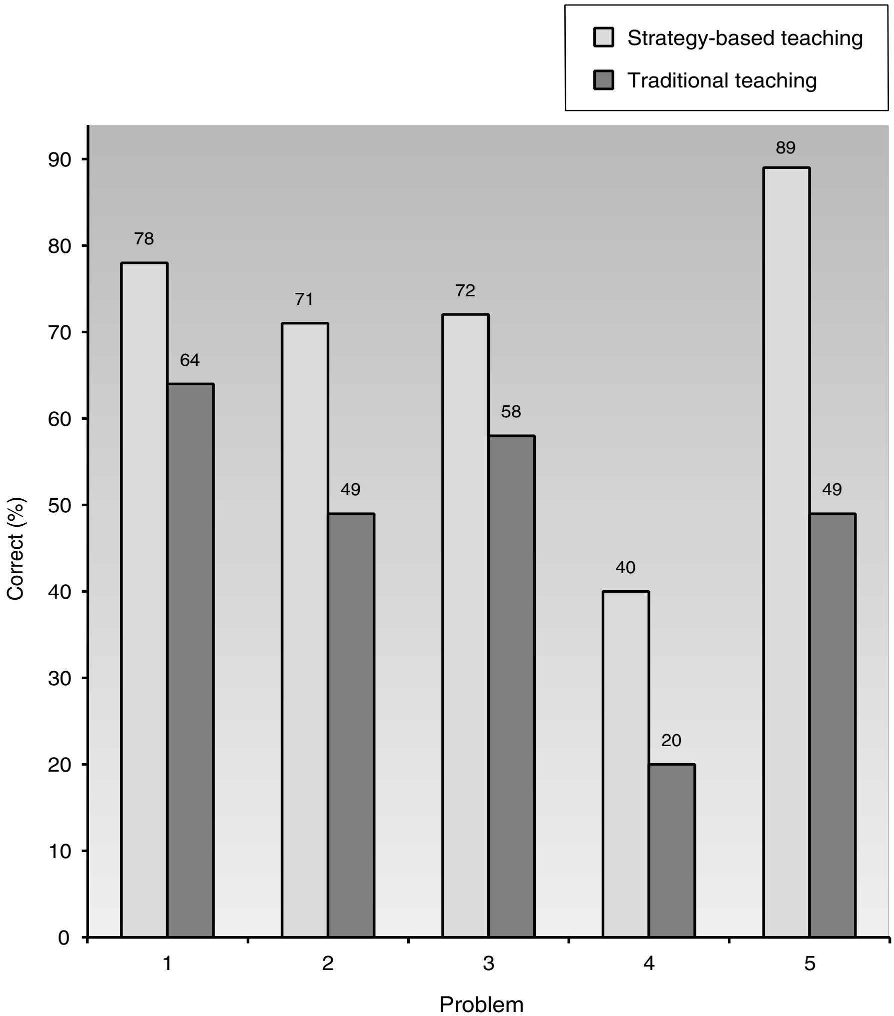


FIGURE 7.3 *Percent correct choices under strategy-based and traditional teaching conditions by problem number in a categorization, multiple-choice task. SOURCE: Dufresne et al. (1992).*

tions needed. In deliberate practice, a student works under a tutor (human or computer based) to rehearse appropriate practices that enhance performance. Through deliberate practice, computer-based tutoring environments have been designed that reduce the time it takes individuals to reach real-world performance criteria from 4 years to 25 hours (see Chapter 9)!

Conceptual Change

Before students can really learn new scientific concepts, they often need to re-conceptualize deeply rooted misconceptions that interfere with the learning. As reviewed above (see Chapters 3 and 4), people spend considerable time and effort constructing a view of the physical world through experiences and observations, and they may cling tenaciously to those views—however much they conflict with scientific concepts—because they help them explain phenomena and make predictions about the world (e.g., why a rock falls faster than a leaf).

One instructional strategy, termed "bridging," has been successful in helping students overcome persistent misconceptions (Brown, 1992; Brown and Clement, 1989; Clement, 1993). The bridging strategy attempts to bridge from students' correct beliefs (called anchoring conceptions) to their misconceptions through a series of intermediate analogous situations. Starting with the anchoring intuition that a spring exerts an upward force on the book resting on it, the student might be asked if a book resting on the middle of a long, "springy" board supported at its two ends experiences an upward force from the board. The fact that the bent board looks as if it is serving the same function as the spring helps many students agree that both the spring and the board exert upward forces on the book. For a student who may not agree that the bent board exerts an upward force on the book, the instructor may ask a student to place her hand on top of a vertical spring and push down and to place her hand on the middle of the springy board and push down. She would then be asked if she experienced an upward force that resisted her push in both cases. Through this type of dynamic probing of students' beliefs, and by helping them come up with ways to resolve conflicting views, students can be guided into constructing a coherent view that is applicable across a wide range of contexts.

Another effective strategy for helping students overcome persistent erroneous beliefs are interactive lecture demonstrations (Sokoloff and Thornton, 1997; Thornton and Sokoloff, 1997). This strategy, which has been used very effectively in large introductory college physics classes, begins with an introduction to a demonstration that the instructor is about to perform, such as a collision between two air carts on an air track, one a stationary light cart, the other a heavy cart moving toward the stationary cart. Each cart has an electronic "force probe" connected to it which displays on a large screen and in real-time the force acting on it during the collision. The teacher first asks the students to discuss the situation with their neighbors and then record a prediction as to whether one of the carts would exert a bigger force on the other during impact or whether the carts would exert equal forces.

The vast majority of students incorrectly predict that the heavier, moving cart exerts a larger force on the lighter, stationary cart. Again, this prediction seems quite reasonable based on experience—students know that a moving

Mack truck colliding with a stationary Volkswagen beetle will result in much more damage done to the Volkswagen, and this is interpreted to mean that the Mack truck must have exerted a larger force on the Volkswagen. Yet, notwithstanding the major damage to the Volkswagen, Newton's Third Law states that two interacting bodies exert equal and opposite forces on each other.

After the students make and record their predictions, the instructor performs the demonstration, and the students see on the screen that the force probes record forces of equal magnitude but oppositely directed during the collision. Several other situations are discussed in the same way: What if the two carts had been moving toward each other at the same speed? What if the situation is reversed so that the heavy cart is stationary and the light cart is moving toward it? Students make predictions and then see the actual forces between the carts displayed as they collide. In all cases, students see that the carts exert equal and opposite forces on each other, and with the help of a discussion moderated by the instructor, the students begin to build a consistent view of Newton's Third Law that incorporates their observations and experiences.

Consistent with the research on providing feedback (see Chapter 3), there is other research that suggests that students' witnessing the force displayed in real-time as the two carts collide helps them overcome their misconceptions; delays of as little as 20-30 minutes in displaying graphic data of an event occurring in real-time significantly inhibits the learning of the underlying concept (Brasell, 1987).

Both bridging and the interactive demonstration strategies have been shown to be effective at helping students permanently overcome misconceptions. This finding is a major breakthrough in teaching science, since so much research indicates that students often can parrot back correct answers on a test that might be erroneously interpreted as displaying the eradication of a misconception, but the same misconception often resurfaces when students are probed weeks or months later (see Mestre, 1994, for a review).

Teaching as Coaching

One of the best examples of translating research into practice is Minstrell's (1982, 1989, 1992) work with high school physics students. Minstrell uses many research-based instructional techniques (e.g., bridging, making students' thinking visible, facilitating students' ability to restructure their own knowledge) to teach physics for understanding. He does this through classroom discussions in which students construct understanding by making sense of physics concepts, with Minstrell playing a coaching role. The following quote exemplifies his innovative and effective instructional strategies (Minstrell, 1989:130-131):

> Students' initial ideas about mechanics are like strands of yarn, some unconnected, some loosely interwoven. The act of instruction can be viewed as helping the students unravel individual strands of belief, label them, and then weave them into a fabric of more complete understanding. An important point is that later understanding can be constructed, to a considerable extent, from earlier beliefs. Sometimes new strands of belief are introduced, but rarely is an earlier belief pulled out and replaced. Rather than denying the relevancy of a belief, teachers might do better by helping students differentiate their present ideas from and integrate them into conceptual beliefs more like those of scientists.

Describing a lesson on force, Minstrell (1989:130-131) begins by introducing the topic in general terms:

> Today we are going to try to explain some rather ordinary events that you might see any day. You will find that you already have many good ideas that will help explain those events. We will find that some of our ideas are similar to those of the scientist, but in other cases our ideas might be different. When we are finished with this unit, I expect that we will have a much clearer idea of how scientists explain those events, and I know that you will feel more comfortable about your explanations . . . A key idea we are going to use is the idea of force. What does the idea of force mean to you?

Many views emerge from the ensuing classroom discussion, from the typical "push or pull" to descriptions that include sophisticated terms, such as energy and momentum. At some point Minstrell guides the discussion to a specific example: he drops a rock and asks students how the event can be explained using their ideas about force. He asks students to individually formulate their ideas and to draw a diagram showing the major forces on the rock as arrows, with labels to denote the cause of each force. A lengthy discussion follows in which students present their views, views that contain many irrelevant (e.g., nuclear forces) or fictitious forces (e.g., the spin of the earth, air). In his coaching, Minstrell asks students to justify their choices by asking questions, such as "How do you know?" "How did you decide?" "Why do you believe that?"

With this approach, Minstrell has been able to identify many erroneous beliefs of students that stand in the way of conceptual understanding. One example is the belief that only active agents (e.g., people) can exert forces, that passive agents (e.g., a table) cannot. Minstrell (1992) has developed a framework that helps both to make sense of students' reasoning and to design instructional strategies. (For a related theoretical framework for classifying and explaining student reasoning, see the discussion of "phenomenological primitives" in DiSessa, 1988, 1993.) Minstrell describes identifiable pieces of students' knowledge as "facets," a facet being a convenient unit of thought, a piece of knowledge, or a strategy seemingly used by the student in addressing a particular situation. Facets may relate to conceptual knowledge (e.g., passive objects do not exert force), to strategic knowledge (e.g., average velocity can be determined by adding the initial and final velocities and dividing by two), or generic reasoning (e.g., the more the X, the more the Y). Identifying students' facets, what cues them in different contexts, and how students use them in reasoning are all helpful in devising instructional strategies.

Interactive Instruction in Large Classes

One of the obstacles to instructional innovation in large introductory science courses at the college level is the sheer number of students who are taught at one time. How does an instructor provide an active learning experience, provide feedback, accommodate different learning styles, make students' thinking visible, and provide scaffolding and tailored instruction to meet specific student needs when facing more than 100 students at a time? Classroom communication systems can help the instructor of a large class accomplish these objectives. One such system, called Classtalk, consists of both hardware and software that allows up to four students to share an input device (e.g., a fairly inexpensive graphing calculator) to "sign on" to a classroom communication network that permits the instructor to send questions for students to work on and permits students to enter answers through their input device. Answers can then be displayed anonymously in histogram form to the class, and a permanent record of each student's response is recorded to help evaluate progress as well as the effectiveness of instruction.

This technology has been used successfully at the University of Massachusetts-Amherst to teach physics to a range of students, from non-science majors to engineering and science majors (Dufresne et al., 1996; Wenk et al., 1997; Mestre et al., 1997). The technology creates an interactive learning environment in the lectures: students work collaboratively on conceptual questions, and the histogram of students' answers is used as a visual springboard for classwide discussions when students defend the reasoning they used to arrive at their answers. This technology makes students' thinking visible and promotes critical listening, evaluation, and argumentation in the class. The teacher is a coach, providing scaffolding where needed, tailoring "mini-lectures" to clear up points of confusion, or, if things are going well, simply moderating the discussion and allowing students to figure out things and reach consensus on their own. The technology is also a natural mechanism to support formative assessment during instruction, providing both the teacher and students with feedback on how well the class is grasping the concepts under study. The approach accommodates a wider variety of learning styles than is possible by lectures and helps to foster a community of learners focused on common objectives and goals.

Science for All Children

The examples above present some effective strategies for teaching and learning science for high school and college students. We drew some general principles of learning from these examples and stressed that the findings consistently point to the strong effect of knowledge structures on learning. These studies also emphasize the importance of class discussions for developing a language for talking about scientific ideas, for making students' thinking explicit to the teacher and to the rest of the class, and for learning to develop a line of argumentation that uses what one has learned to solve problems and explain phenomena and observations.

The question that immediately occurs is how to teach science to younger children or to students who are considered to be educationally "at risk." One approach that has been especially useful in science teaching was developed with language-minority grade-school children: Chèche Konnen, which in Haitian Creole means search for knowledge (Rosebery et al., 1992). The approach stresses how discourse is a primary means for the search for knowledge and scientific sense-making. It also illustrates how scientific ideas are constructed. In this way it mirrors science, in the words of Nobel Laureate Sir Peter Medawar (1982:111):

> Like other exploratory processes, [the scientific method] can be resolved into a dialogue between fact and fancy, the actual and the possible; between what could be true and what is in fact the case. The purpose of scientific enquiry is not to compile an inventory of factual information, nor to build up a totalitarian world picture of Natural Laws in which every event that is not compulsory is forbidden. We should think of it rather as a logically articulated structure of justifiable beliefs about a Possible World—a story which we invent and criticize and modify as we go along, so that it ends by being, as nearly as we can make it, a story about real life.

The Chèche Konnen approach to teaching began by creating "communities of scientific practice" in language-minority classrooms in a few Boston and Cambridge, MA public schools. "Curriculum" emerges in these classrooms from the students' questions and beliefs and is shaped in ongoing interactions that include both the teacher and students. Students explore their own questions, much as we described above in Barb Johnson's class. In addition, students design studies, collect information, analyze data and construct evidence, and they then debate the conclusions that *they* derive from their evidence. In effect, the students build and argue about theories; see Box 7.5.

Students constructed scientific understandings through an iterative process of theory building, criticism, and refinement based on their own questions, hypotheses, and data analysis activities. Question posing, theorizing, and argumentation formed the structure of the students' scientific activity.

Within this structure, students explored the implications of the theories they held, examined underlying assumptions, formulated and tested hypotheses, developed evidence, negotiated conflicts in belief and evidence, argued alternative interpretations, provided warrants for conclusions, and so forth. The process as a whole provided a richer, more scientifically grounded experience than the conventional focus on textbooks or laboratory demonstrations.

The emphasis on establishing communities of scientific practice builds on the fact that robust knowledge and understandings are socially constructed through talk, activity, and interaction around meaningful problems and tools (Vygotsky, 1978). The teacher guides and supports students as they explore problems and define questions that are of interest to them. A community of practice also provides direct cognitive and social support for the efforts of the group's individual members. Students share the responsibility for thinking and doing: they distribute their intellectual activity so that the burden of managing the whole process does not fall to any one individual. In addition, a community of practice can be a powerful context for constructing scientific meanings. In challenging one another's thoughts and beliefs, students must be explicit about their meanings; they must negotiate conflicts in belief or evidence; and they must share and synthesize their knowledge to achieve understanding (Brown and Palincsar, 1989; Inagaki and Hatano, 1987).

What do students learn from participating in a scientific sense-making community? Individual interviews with students before and after the water taste test investigation (see Box 7.4), first in September and again the following June, showed how the students' knowledge and reasoning changed. In the interviews (conducted in Haitian Creole), the students were asked to think aloud about two open-ended real-world problems—pollution in the Boston Harbor and a sudden illness in an elementary school. The researchers were interested in changes in students' conceptual knowledge about aquatic ecosystems and in students' uses of hypotheses, experiments, and explanations to organize their reasoning (for a complete discussion, see Rosebery et al., 1992).

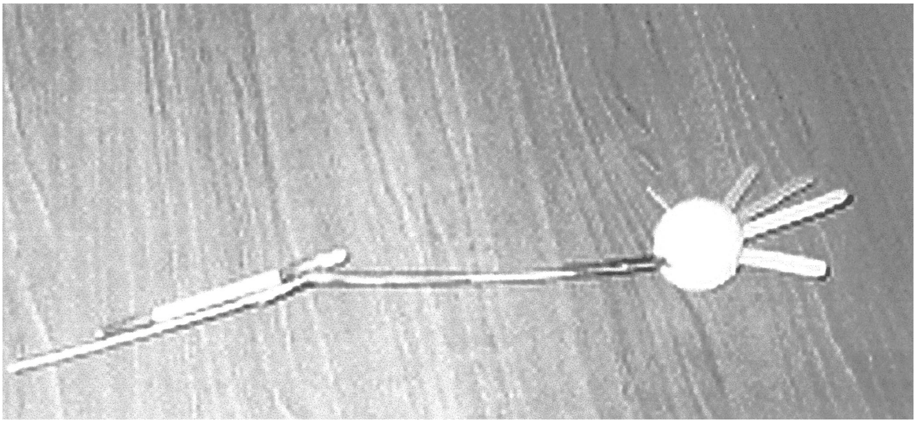
Conceptual Knowledge

Not surprisingly, the students knew more about water pollution and aquatic ecosystems in June than they did in September. They were also able to use this knowledge generatively. One student explained how she would clean the water in Boston Harbor (Rosebery et al., 1992:86).

> Like you look for the things, take the garbage out of the water, you put a screen to block all the paper and stuff, then you clean the water; you put chemical products in it to clean the water, and you'd take all the micro-

BOX 7.5 Physical Models

Physical models, like models of solar systems or elbows, are microcosms of systems that draw heavily on children's intuitions about resemblance to sustain the relationship between the world being modeled and the model itself. The photograph below displays a child's model of the elbow. Note, for instance, the rubber bands that mimic the connective function of ligaments and the wooden dowels that are arranged so that their translation in the vertical plane cannot exceed 180 degrees. Though the search for function is supported by initial resemblance, what counts as resemblance typically changes as children revise their models. For example, attempts to make models exemplify elbow motion often lead to an interest in the way muscles might be arranged (from Lehrer and Schauble, 1996a, b).



Child's Model of an Elbow

> scopic life out. Chlorine and alum, you put in the water. They'd gather the little stuff, the little stuff would stick to the chemical products, and they would clean the water.

Note that this explanation contains misconceptions. By confusing the cleaning of drinking water with the cleaning of sea water, the student suggests adding chemicals to take all microscopic life from the water (good for drinking water, but bad for the ecosystem of Boston Harbor). This example illustrates the difficulties in transferring knowledge appropriately from one context to another (see Chapter 3). Despite these shortcomings, it is clear that this student is starting on the path to scientific thinking, leaving behind the more superficial "I'd take all the bad stuff out of the water" type of explanation. It is also clear that by making the student's thinking visible, the teacher is in an excellent position to refine her (and perhaps the class's) understanding.

Scientific Thinking

Striking changes appeared in students' scientific reasoning. In September, there were three ways in which the students showed little familiarity with scientific forms of reasoning. First, the students did not understand the function of hypotheses or experiments in scientific inquiry. When asked for their ideas about what could be making the children sick, the students tended, with few exceptions, to respond with short, unelaborated, often untestable "hypotheses" that simply restated the phenomena described in the problem: "That's a thing . . . . Ah, I could say a person, some person that gave them something . . . . Anything, like give poison to make his stomach hurt" (Rosebery et al., 1992:81).

Second, the students conceptualized evidence as information they already knew, either through personal experience or second-hand sources, rather than data produced through experimentation or observation. When asked to generate an experiment to justify an hypothesis—"How would you find out?"—they typically offered declarations: "Because the garbage is a poison for them . . . . The garbage made the fish die" (Rosebery et al., 1992:78).

Third, the students interpreted an elicitation for an experiment—"How would you be sure?"—as a text comprehension question for which there was a "right" answer. They frequently responded with an explanation or assertion of knowledge and consistently marked their responses as explanatory ("because"): "Because fish don't eat garbage. They eat plants under the water" (page 78).

In the June interviews, the students showed that they had become familiar with the function of hypotheses and experiments and with reasoning within larger explanatory frameworks. Elinor had developed a model of an integrated water system in which an action or event in one part of the system had consequences for other parts (Rosebery et al., 1992:87):

> You can't leave [the bad stuff] on the ground. If you leave it on the ground, the water that, the earth has water underground, it will still spoil the water underground. Or when it rains it will just take it and, when it rains, the water runs, it will take it and leave it in the river, in where the water goes in. Those things, poison things, you aren't supposed to leave it on the ground.

In June, the students no longer invoked anonymous agents, but put forward chains of hypotheses to explain phenomena, such as why children were getting sick (page 88):

> Like, you could test what the kids ate and, like, test the water, too; it could be the water that isn't good, that has microbes, that might have microscopic animals in it to make them sick.

The June interviews also showed that students had begun to develop a sense of the function and form of experimentation. They no longer depended on personal experience as evidence, but proposed experiments to test specific hypotheses. In response to a question about sick fish, Laure clearly understands how to find a scientific answer (page 91):

> I'd put a fish in fresh water and one fish in a water full of garbage. I'd give the fresh water fish food to eat and the other one in the nasty water, I'd give it food to eat to see if the fresh water, if the one in the fresh water would die with the food I gave it, if the one in the dirty water would die with the food I gave it. . . . I would give them the same food to see if the things they eat in the water and the things I give them now, which will make them healthy and which wouldn't make them healthy.

Conclusion

Teaching and learning in science have been influenced very directly by research studies on expertise (see Chapter 2). The examples discussed in this chapter focus on two areas of science teaching: physics and junior high school biology. Several of the teaching strategies illustrated ways to help students think about the general principles or "big" ideas in physics before jumping to formulas and equations. Others illustrate ways to help students engage in deliberate practice (see Chapter 3) and to monitor their progress.

Learning the strategies for scientific thinking have another objective: to develop thinking acumen needed to promote conceptual change. Often, the barrier to achieving insights to new solutions is rooted in a fundamental misconception about the subject matter. One strategy for helping students in physics begins with an "anchoring intuition" about a phenomenon and then gradually bridging it to related phenomena that are less intuitive to the student but involve the same physics principles. Another strategy involves the use of interactive lecture demonstrations to encourage students to make predictions, consider feedback, and then reconceptualize phenomena.

The example of Chèche Konnen demonstrates the power of a sense-making approach to science learning that builds on the knowledge that students bring with them to school from their home cultures, including their familiar discourse practices. Students learned to think, talk, and act scientifically, and their first and second languages mediated their learning in powerful ways. Using Haitian Creole, they designed their studies, interpreted data, and argued theories; using English, they collected data from their mainstream peers, read standards to interpret their scientific test results, reported their findings, and consulted with experts at the local water treatment facility.

CONCLUSION

Outstanding teaching requires teachers to have a deep understanding of the subject matter and its structure, as well as an equally thorough understanding of the kinds of teaching activities that help students understand the subject matter in order to be capable of asking probing questions.

Numerous studies demonstrate that the curriculum and its tools, including textbooks, need to be dissected and discussed in the larger contexts and framework of a discipline. In order to be able to provide such guidance, teachers themselves need a thorough understanding of the subject domain and the epistemology that guides the discipline (for history, see Wineburg and Wilson, 1988; for math and English, see Ball, 1993; Grossman et al., 1989; for science, see Rosebery et al., 1992).

The examples in this chapter illustrate the principles for the design of learning environments that were discussed in Chapter 6: they are learner, knowledge, assessment, and community centered. They are learner centered in the sense that teachers build on the knowledge students bring to the learning situation. They are knowledge centered in the sense that the teachers attempt to help students develop an organized understanding of important concepts in each discipline. They are assessment centered in the sense that the teachers attempt to make students' thinking visible so that ideas can be discussed and clarified, such as having students (1) present their arguments in debates, (2) discuss their solutions to problems at a qualitative level, and (3) make predictions about various phenomena. They are community centered in the sense that the teachers establish classroom norms that learning with understanding is valued and students feel free to explore what they do not understand.

These examples illustrate the importance of pedagogical content knowledge to guide teachers. Expert teachers have a firm understanding of their respective disciplines, knowledge of the conceptual barriers that students face in learning about the discipline, and knowledge of effective strategies for working with students. Teachers' knowledge of their disciplines provides a cognitive roadmap to guide their assignments to students, to gauge student progress, and to support the questions students ask. The teachers focus on understanding rather than memorization and routine procedures to follow, and they engage students in activities that help students reflect on their own learning and understanding.

The interplay between content knowledge and pedagogical knowledge illustrated in this chapter contradicts a commonly held misconception about teaching—that effective teaching consists of a set of general teaching strategies that apply to all content areas. This notion is erroneous, just as is the idea that expertise in a discipline is a general set of problem-solving skills that lack a content knowledge base to support them (see Chapter 2).

The outcomes of new approaches to teaching as reflected in the results of summative assessments are encouraging. Studies of students' discussions in classrooms indicate that they learn to use the tools of systematic inquiry to think historically, mathematically, and scientifically. How these kinds of teaching strategies reveal themselves on typical standardized tests is another matter. In some cases there is evidence that teaching for understanding can increase scores on standardized measures (e.g., Resnick et al., 1991); in other cases, scores on standardized tests are unaffected, but the students show sizable advantages on assessments that are sensitive to their comprehension and understanding rather than reflecting sheer memorization (e.g., Carpenter et al., 1996; Secules et al., 1997).

It is noteworthy that none of the teachers discussed in this chapter felt that he or she was finished learning. Many discussed their work as involving a lifelong and continuing struggle to understand and improve. What opportunities do teachers have to improve their practice? The next chapter explores teachers' chances to improve and advance their knowledge in order to function as effective professionals.

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CHAPTER 5

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CHAPTER 11

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COMMITTEE ON DEVELOPMENTS IN THE SCIENCE OF LEARNING

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Acknowledgments

A good deal of the excitement surrounding the project that resulted in the original version of this volume was due to people's seeing the relevance of basic science to education. In light of that connection, the committee held a workshop in fall 1996—"The Science of Science Learning"—to broaden its understanding of the influences that cognitive science has had on science and mathematics learning and teaching. We benefited greatly from the stimulating papers and discussions that grew out of that meeting, as have others who since have used the model of the workshop. We extend our thanks especially to the following people who presented papers and led discussions during the workshop: Susan Carey, Department of Psychology, New York University; Orville L. Chapman, Department of Chemistry, University of California, Los Angeles; Kevin Dunbar, Psychology Department, McGill University; Jill H. Larkin, Department of Psychology, Carnegie-Mellon University; Kevin Miller, Beckman Institute, University of Illinois; Edward F. Redish, Department of Physics and Astronomy, University of Maryland; Leona Schauble, Department of Educational Psychology, University of Wisconsin, Madison; Lee S. Shulman, Stanford University School of Education; Herbert A. Simon, Department of Psychology, Carnegie-Mellon University; and Philip Uri Treisman, Dana Center for Mathematics and Science Education, University of Texas, Austin.

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Although the project was an intellectually exciting undertaking for the committee, we were also mindful of the important role of our sponsor. The Office of Educational Research and Improvement (OERI) of the U.S. Department of Education established the committee's charge to review the nation's investment in research and the challenge of determining how that investment can pay high returns. We thank Joseph Conaty, Judith Segal, and C. Kent McGuire for the support they provided to this committee in their individual and official capacities.

Finally, there are several NRC staff and others who made significant contributions to the work of the Committee on Developments in the Science of Learning. Alexandra Wigdor, director of the Division of Education, Labor, and Human Performance of the NRC's Commission on Behavioral and Social Sciences and Education (CBASSE), provided the initial impetus for the project and nurtured it in many different ways that were indispensable to its completion. Eugenia Grohman, associate director for reports of CBASSE, patiently worked with us through several drafts of the volume and significantly improved the text. Key support in facilitating our work came from Jane Phillips, senior project assistant in CBASSE, with assistance from Neale Baxter; Susan M. Coke, division administrative associate; Faapio Poe, administrative assistant, Vanderbilt University; and Carol Cannon, administrative assistant, University of California, Berkeley. All of these "behind the scenes" people played critical roles, and to each of them we are very grateful.

Alexandra Wigdor also was the inspiration for the project that resulted in *How People Learn: Bridging Research and Practice*. Her leadership in guiding the formation and work of the Committee on Learning Research and Educational Practice was central to its success. The vision of focusing the efforts of the research community on classroom practice is that of C. Kent McGuire, assistant secretary for educational research and improvement at the U.S. Department of Education. Rodney Cocking, study director of the Committee on Developments in the Science of Learning, provided support for the efforts of the Committee on Learning Research and Educational Practice. Wendell Grant, project assistant, worked long hours managing the logistics of the latter committee's meetings and events and providing the administrative support for production of the committee's report and its drafts. Christine McShane improved that report with her skilled editing. We also thank Carolyn Stalcup for design support and Sandra Yurchak for secretarial support.

The Committee on Learning Research and Educational Practice held a conference in December 1998 to present the original version of *How People Learn* to an audience of educators, policy makers, and researchers and to elicit their feedback on the promise of, and obstacles to, bridging educational research and practice. The NRC and the OERI cosponsored the conference, and the participation of Bruce Alberts, NRC chair, and C. Kent McGuire, assistant secretary for OERI, contributed to its success. Joseph Conaty and Luna Levinson of OERI assisted with conference planning. Karen Fuson, committee member Annemarie Palincsar, and Robert Bain demonstrated approaches to teaching that use the principles highlighted in this volume. Members of the two panels provided insightful perspectives on the challenge of bridging research and classroom practice. On the panel providing teacher perspectives were David Berliner, Deanna Burney, Janice Jackson, Jean Krusi, Lucy (Mahon) West, and Robert Morse. On the panel providing policy perspectives were Ron Cowell, Louis Gomez, Paul Goren, Jack Jennings, Kerri Mazzoni, and Carol Stewart.

The committee also held a workshop to focus more sharply on the research that would help construct the bridge between research and practice. The workshop was an intensive 2-day effort to work in both large and small groups to cover the areas of research discussed in this volume. We thank each of the participants who joined the committee in this effort: Amy Alvarado, Karen Bachofer, Robert Bain, Cathy Cerveny, Cathy Colglazier, Rodney Cocking, Ron Cowell, Jean Krusi, Luna Levinson, Robert Morse, Barbara Scott Nelson, Iris Rotberg, Leona Schauble, Carol Stewart, and Lucy West.

Both the original version of *How People Learn: Brain, Mind, Experiences, and School* and *How People Learn: Bridging Research and Practice* were reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the Report Review Committee of the National Research Council (NRC). The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The content of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

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John D. Bransford, James Pellegrino,
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