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:

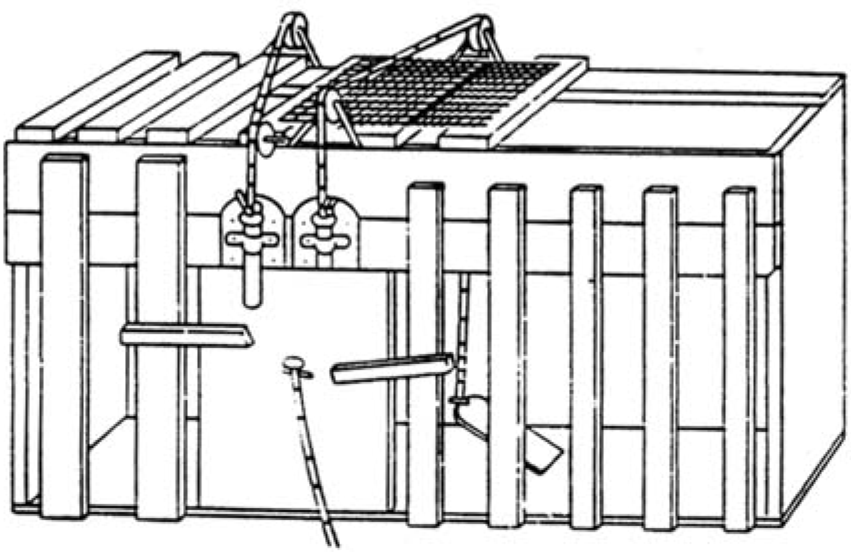
… all schools of psychology except that of behaviorism claim that "consciousness" is the subject-matter of psychology. Behaviorism, on the contrary, holds that the subject matter of human psychology is the behavior or activities of the human being. Behaviorism claims that "consciousness" is neither a 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, in press). 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 active 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 report.

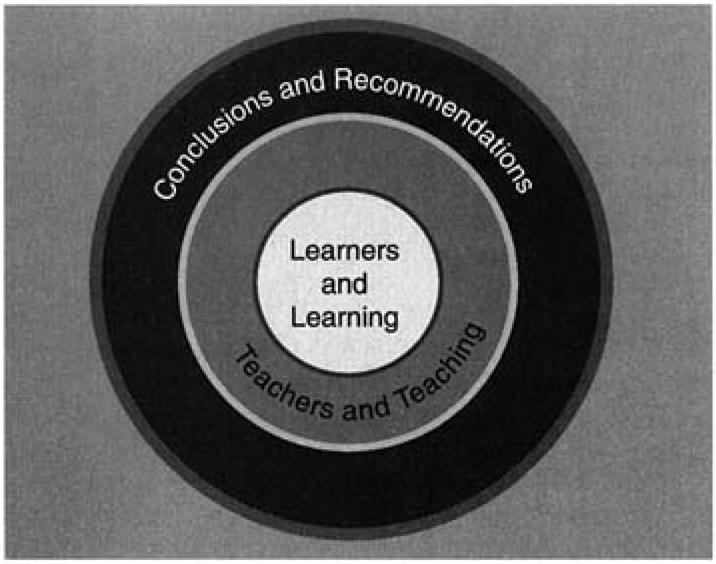


FIGURE 1.1

Report Overview

It is important to keep in mind that there has been a longer history of rigorous research on issues of learners and learning (Chapters 2–5) than on the design of learning environments and the implications of technology (Chapters 6–9). Research on classroom-based learning and teacher learning (especially the many opportunities for informal learning) often use newer qualitative methodologies, such as ethnography and case-study analysis, to capture the richness of learning in context. A rigorous methodology has been developed for conducting such studies (e.g., see Erickson, 1986; Hammersly and Atkinson, 1983; Heath, 1982; Lincoln and Guba, 1985; Marshall and Rossman, 1955; Miles and Huberman, 1984; Spradley, 1979).

Chapter 2, on expertise, discusses lessons learned from studies of people who have become experts in areas such as chess, physics, mathematics, or history. What is known about experts is important not because all students are expected to become experts, but because the knowledge of expertise provides valuable insights into what the results of effective learning look like.

Chapter 3 moves from what is known about experts to an examination of processes of learning that underlie effective knowledge acquisition. Special emphasis is placed on understanding the kinds of learning experiences that lead to transfer—the ability to use what was learned in one setting to deal with new problems and events.

Chapter 4 extends the examination of learning to infants and young children. Data show that children's early competencies in areas such as causal relationships, numbers, and language are much more sophisticated

than was previously believed. These competencies provide the foundations for important concepts and ideas that children build on in later learning.

Chapter 5 explores new developments in neuroscience, while providing some cautionary advice about a number of popular myths that should not influence education. Neuroscience provides converging evidence about processes of learning and development and enriches understanding of learning by explicating the mechanisms by which learning occurs.

Chapter 6 explores general principles for the design of effective learning environments that are suggested by the science of learning. It explores the degree to which environments are learner centered, knowledge centered, assessment centered, and community centered. These components must be brought into alignment in order for effective change to occur.

Chapter 7 presents examples of effective teaching practices that are consistent with new knowledge about learning. We present contrasting illustrations of effective teaching in history, mathematics, and science. Effective teaching practices vary across subjects because knowledge in different subjects is organized differently and based on different ways of knowing (epistemologies).

Chapter 8 explores teacher learning—which includes both practicing teachers and college students studying to be teachers. The science of learning has important implications for helping teachers continue to learn throughout their lives.

Chapter 9 presents promising new developments in technology that have the potential to provide new possibilities for enhancing learning. We discuss data on technology and learning when they exist, but we also discuss new possibilities that future research should explore.

Chapter 10 concludes our study with a summary of the major findings of the study on learners and learning, teachers and teaching, and learning environments and recommends new areas of research.