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ABSTRACT

A project of the Center for the Study of Learning at the University of Pittsburgh, this yearbook combines the two major trends/concerns impacting the future of educational development for the next decade: knowledge and thinking. The yearbook comprises the following chapters: (1) "Toward the Thinking Curriculum: An Overview" (Lauren B. Resnick and Leopold E. Klopfer); (2) "Instruction for Self-Regulated Reading" (Annemarie Sullivan Palincsar and Ann L. Brown); (3) "Improving Practice through Understanding Reading" (Isabel L. Beck); (4) "Teaching Mathematics Concepts" (Rochelle G. Kaplan and others); (5) "Teaching Mathematical Thinking and Problem Solving" (Alan H. Schoenfeld); (6) "Research on Writing: Building a Cognitive and Social Understanding of Composing" (Glynda Ann Hull); (7) "Teaching Science for Understanding" (James A. Minstrell); (8) "Research on Teaching Scientific Thinking: Implications for Computer-Based Instruction" (Jill H. Larkin and Ruth W. Chabay); and (9) "A Perspective on Cognitive Research and Its Implications for Instruction" (John D. Bransford and Nancy J. Vye). (MS)

Toward the Thinking Curriculum: Current Cognitive Research

1989 Yearbook of the Association for Supervision and Curriculum Development

edited by Lauren B. Resnick
and Leopold E. Klopfer

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Over the last three years, many people have played a role in planning and preparing the 1989 ASCD yearbook. A CSL planning committee composed of Isabel Beck, William Bickel, and Gaea Leinhardt provided editorial advice for the project. We are grateful for the substantive chapter reviews provided by Isabel Beck, Michelene Chi, Margaret McKeown, Charles Perfetti, Miriam Reiner, Leona Schauble, Edward Silver, and Joanne Striley. And we appreciate the efforts of Ronald Brandt and the ASCD staff who have worked with us throughout.

LAUREN B. RESNICK
LEOPOLD E. KLOPFER

Foreword

A Curriculum . . . is the enterprise par excellence where the line between subject matter and the method grows necessarily indistinct
—Jerome Bruner

Curriculum decision makers are plagued with conflicting admonitions about what should be taught. Scholars such as Hirsch, Cheney, Ravitch, Finn, and Bennett have argued that disciplinary knowledge and cultural literacy are the primary ingredients for achieving an educated citizenry. They contend that the most effective contribution schools can make is to deliver the major concepts and understandings needed by all citizens.

As a result of this knowledge-oriented standard for literacy, coupled with the information explosion, schools have been pressured to expand the breadth and depth of subject matter coverage. Organizationally, schools have been judged "reformed" because they have increased the number of class periods per week and required more minutes per day or more days per year. Teachers' decision making has been influenced by curriculum guidelines, textbook adoptions, and testing programs. Parents and politicians have come to judge schools and educators by their ability to impart more knowledge sooner and faster. Teachers are thereby persuaded that the more content covered, the more effective is their teaching. A corollary of this belief is that the more rapidly and rigorously students progress through the curriculum, the more effective the instruction. Thus, the most effective instruction has become defined in terms of "coverage."

In contrast to those who assert that the new standards for literacy will best be met by increasing the emphasis on knowledge, other educators believe that such knowledge in and of itself may be of little use. Rather, what is needed is to emphasize the teaching of thinking processes and skills. These educators assert that the tools of inquiry by which one discovers and validates knowledge are the transferable results of school and, consequently, emphasis should be given to developing these skills using disciplinary and cultural knowledge as a means, not an end, for educating a literate citizenry.

The many educators in this camp believe that the passing of the industrial era means the passing of the usefulness of standardization as an organizing educational principle. "What *all* literate citizens should know" will no longer be a major concern. It is not possible to predict exactly the knowledge base required of productive citizens in the global/service-oriented/information age. It is also impossible to "cover" all the information in a human's lifetime. We can be sure, though, that all citizens will need to solve problems, to think creatively, and to continue to learn.

This yearbook is dedicated to strengthening educational leaders who are buffeted by conflicting demands and beliefs. It combines the two major trends/concerns impacting the future of educational development for the next decade: knowledge and thinking. Rather than polarize these two educational necessities, it integrates them.

This yearbook includes contributions from noted theorists, practitioners, and scholars who have demonstrated abilities to define the key concepts of their disciplines and link them to the modes of thinking, dispositions, and tools of inquiry that are basic to those disciplines. They offer a rich background of research and practical ideas to help us address such intriguing questions as:

1. Which of the tools of inquiry are important and why?
2. Why are modes of inquiry and thinking important in understanding and in teaching school subjects?
3. How do modes of thinking intersect with the knowledge base in a subject?
4. What instructional processes best develop subject matter concepts in students?

From the presentations in this volume, additional questions that intrigue curriculum decision makers will no doubt emerge:

1. How much time should be spent teaching various concepts and at what developmental ages are they best taught?
2. How are these concepts and modes of inquiry organized to be reinforced throughout the curriculum and the school?
3. How can we help preservice and inservice teachers understand the concepts, modes of inquiry, and thought processes, and how to teach them.
4. Which of the modes of thinking and tools of inquiry are generalizable to other subjects and to daily life?
5. How can we measure and report growth in thinking abilities?

As we draw nearer to the 21st century, as knowledge continues to accumulate, and as education becomes a key criterion for comparing our level of development with that of other countries, this ASCD yearbook makes a valuable contribution to educational decision making.

ARTHUR L. COSTA
ASCD President, 1988-89

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Toward the Thinking Curriculum: An Overview

Lauren B. Resnick and Leopold E. Klopfer

As we enter the 1990s, thoughtful educators everywhere are calling attention to the importance of developing students' thinking skills through their experiences in school. We are witnessing the growth of a remarkable consensus that the achievement of basic literacy, while obviously necessary, is not a sufficient goal, and that students have the right to expect more from elementary and secondary education. Graduates must not only be literate; they must also be competent thinkers.

The goal of having students become competent thinkers has long been an educational ideal. And, for just as long, this ideal has eluded too many students in too many schools. Recent research, however, provides a new perspective on how people learn to think. Pursuing these new ideas may provide the basis for future educational practices that can help students become skilled in thinking.

One of the most significant ideas emerging from recent research on thinking is that the mental processes we have customarily associated with thinking are not restricted to some advanced or "higher order" stage of mental development. Instead, "thinking skills" are intimately involved in successful learning of even elementary levels of reading, mathematics, and other subjects. Cognitive research on children's learning of basic skills such as reading and arithmetic reveals that cultivating key aspects of these thinking processes can and should be an intrinsic part of good instruction from the beginning of school. Thinking, it appears, must pervade the entire school curriculum, for all students, from the earliest grades.

This yearbook is about the Thinking Curriculum. The Thinking Curriculum is not a course to be added to a crowded program when time permits. It is not a program that begins after the "basics" have been mastered. And it is not a program reserved for a minority of students, such as the gifted or the college bound. The Thinking Curriculum calls for a recognition that all real learning involves thinking, that thinking ability can be nurtured and cultivated in everyone, and that the entire educational program must be reconceived and revitalized so that thinking pervades students' lives from kindergarten onward, in mathematics and history class, in reading and science, in composition and art, in vocational and special education.

Psychology and Educational Practice

The chapters in this book are all informed by recent developments in cognitive psychology and related fields. Today's cognitive psychology may be unfamiliar to educators whose experience with educational psychology is more than a decade or two old.

For many years, mainstream educational practice was informed by a psychology of learning that lived only uncomfortably with the mind or with thinking. Derived from associationist and behaviorist principles, it took learning to be an accumulation of pieces of knowledge and bits of skill. This knowledge could be analyzed into hundreds of components ("associations," in the technical language), to be placed in learners' heads through practice and appropriate rewards. Theories of classroom management, textbook design, and organization of practice all flowed from this basic assumption. Successive refinements of associationist and behaviorist educational psychology, recognizing layers of complexity and difficulty in the knowledge and skills to be learned, proposed hierarchies of objectives or forms of learning—as in the widely-known hierarchies of Benjamin Bloom and Robert Gagne (Bloom 1954, 1964, Gagne 1974). Problem solving and other activities recognizable as thinking took their place at the top of these hierarchies, which helped to keep alive the idea that there was more to education than acquiring bodies of facts and associations. But these theories isolated thinking and problem solving from the main, the "basic" or "fundamental," activities of learning.

Thinking and reasoning became not the heart of education but hoped-for capstones that many students never reached.

There were, of course, challengers to the dominant view. For example, Jean Piaget and his followers have argued for over 50 years that knowledge acquired by memorizing is not real knowledge that can be used (e.g., Piaget 1948/1974). Piaget gave us a picture of the "natural" child as a scientist trying to make sense of the world, and of true learning as constructing ideas, not memorizing information in the forms given by teachers or texts. A similar critique was offered by Gestalt psychologists such as Max Wertheimer, who showed that practiced performance in school often masked failure to understand why procedures worked and inability to adapt to modifications in how problems were presented (Wertheimer 1945/1959).[1]

However, these critiques were difficult to adopt into a mainstream program organized for practiced performances and demonstrations of mastery on school tests. One reason was that Piagetian and Gestalt theories of thinking seemed to deny the importance of specific knowledge and to set cultivation of thinking skills apart from learning subject matter. This is illustrated by the difficulties educators experienced in adopting Piagetian theory even in areas where it had its greatest influence: early childhood and science education. In the former, Piagetian theory stressed the need for children to develop understanding through their own constructive activities and at their own natural rates of development. It was no simple matter—and one never fully resolved—to figure out how to incorporate teaching of important knowledge (the alphabet principle applied to reading, for example, or fundamental arithmetic concepts) within the constraints of a program that fundamentally mistrusted all attempts to instruct directly. In science education, the Piagetian interpretation led to a major emphasis on hands-on laboratories and process skills, but these proved difficult to integrate—under Piagetian guidance alone—with the scientific knowledge about which reasoning was to occur.

Modern cognitive theory resolves this conflict. It offers a perspective on learning that is thinking- and meaning-centered, yet insists on a central place for knowledge and instruction. Cognitive scientists today share with Piagetians a constructivist view of learning,

[1]A typical example of Wertheimer's observations is recounted in Schoenfeld's chapter in this volume.

asserting that people are not recorders of information but builders of knowledge structures. To know something is not just to have received information but also to have interpreted it and related it to other knowledge. To be skilled is not just to know how to perform some action but also to know when to perform it and to adapt the performance to varied circumstances.

Today's cognitive science does not suggest that educators get out of the way so that children can do their natural work, as Piagetian theory often seemed to imply. Instead, cognitive instructional researchers are developing a new body of instructional theory based on constructivist, self-regulated assumptions about the nature of learning. This instructional theory is concerned with all of the traditional questions of teaching: how to present and sequence information, how to organize practice and feedback, how to motivate students, how to integrate laboratory activities with other forms of learning, how to assess learning. But each of these questions is addressed differently than in traditional instructional theory, for it is assumed that the goal of all of these instructional activities is to stimulate and nourish students' own mental elaborations of knowledge and to help them grow in their capacity to monitor and guide their own learning and thinking. Thinking and learning merge in today's cognitive perspective, so that cognitive instructional theory is, at its very heart, concerned with the Thinking Curriculum.

Some Organizing Themes

This yearbook examines various aspects of cognitive instructional theory for the Thinking Curriculum. Rather than treating thinking as a separate part of the curriculum, it considers how the traditional subject matter of the elementary and secondary school can be taught in ways that engage mental elaboration and self-regulation. Thinking suffuses the curriculum that is proposed and analyzed by these authors. Before introducing the chapters individually, we discuss here some common themes of cognitive instructional theory that recur throughout the book.

The Centrality of Knowledge

Recent cognitive research teaches us to respect knowledge and expertise. Study after study shows that experts on a topic reason more powerfully about that topic and learn new things related to it more easily than they do on other topics. This is true for science, mathematics, political science, technical skills—for all fields of expertise. We learn most easily when we already know enough to have organizing schemas that we can use to interpret and elaborate upon new information.

Expertise tends to increase with age because we acquire more knowledge over time. This knowledge, not just greater maturity, helps older people learn most things more easily. When children acquire unusual levels of knowledge, however, they often perform as well as, or better than, adults on tasks that depend on that knowledge. For example, in one study done by Michelene Chi, 10-year-old children who played tournament chess outperformed adults in their ability to remember positions on a chess board after looking at the board very briefly. These were not exceptionally smart children; when they were asked to remember random displays of chess pieces—rather than sensible positions that would be generated in games—they reverted to ordinary memory span performances of five or six items. It was their superior chess knowledge that produced superior memory performance (Chi 1978). Expertise is relative, of course. An "expert" 10-year-old in a history class does not know as much history as an undergraduate major in the field. Yet, the 10-year-old who knows something about basic principles of representative government is in a far better position to interpret—and, therefore, learn and remember—new information about the Boston Tea Party and other key events of American history than a child without this knowledge.

A fundamental principle of cognition, then, is that learning requires knowledge. Yet, cognitive research also shows that knowledge cannot be given directly to students. Before knowledge becomes truly generative—knowledge that can be used to interpret new situations, to solve problems, to think and reason, and to learn—students must elaborate and question what they are told, examine the new information in relation to other information, and build new knowledge structures. Educators are thus faced with a central problem: how to help students get started in developing their base of generative knowledge so they can learn easily and independently later on.

Several chapters in this yearbook address this problem directly. For example, you will find the problem discussed by Beck, Minstrell, Larkin and Chabay, and Kaplan, Yamamoto, and Ginsburg. None of the authors proposes that simply telling students about key principles or concepts provides usable, truly generative knowledge. For key concepts and organizing knowledge structures to become generative, they have to be called upon over and over again as ways to link, interpret, and explain new information.

Joining Skill and Content in the Thinking Curriculum

To teach by using concepts generatively is, happily, to teach content and skills of thinking at the same time. This is the real meaning of the Thinking Curriculum, where concepts are continually at work in contexts of reasoning and problem solving. Several chapters in this yearbook—especially those of Palincsar and Brown, Schoenfeld, Hull, and Minstrell—illustrate how standard school subjects can become the primary sites for developing problem solving and reasoning. In this vision of the Thinking Curriculum, thinking suffuses the curriculum. It is everywhere. Thinking skills and subject-matter content are joined early in education and pervade instruction. There is no choice to be made between a content emphasis and a thinking-skill emphasis. No depth in either is possible without the other.

The Thinking Curriculum joins content and skill so intimately that both are everywhere. Does this mean that skills learned in one subject will "transfer" to others? Perhaps. No answer to that question is possible on the basis of current research. Research on transfer has not looked at the effects of instruction that combines practice in thinking with generative content, only at the effects of one or the other alone. Educational practice, however, does not need to wait for an answer to the transfer question before going ahead with the Thinking Curriculum. The decision to exercise thinking in every subject means that, even without transfer, students will have acquired thinking skills of many kinds, usable in many arenas of learning. Transfer, if we can find ways to produce it, will be a welcome additional benefit. But even without it—or with only limited amounts of it—the Thinking Curriculum can be a success.

Joining Cognition and Motivation in the Thinking Curriculum

The Thinking Curriculum must attend not just to teaching skills and knowledge, but also to developing motivation for their use. Substantial amounts of recent research suggest that good thinkers and problem solvers differ from poorer ones not so much in the particular skills they possess as in their tendency to use them. Early research on metacognition was centered on such simple skills as rehearsal and other strategies for memorizing. Several investigators found that retarded children differed from normal ones in their failure to use these skills when given memorization tasks. Yet, to their initial surprise, these investigators discovered that it often took no more than a suggestion that rehearsal or another strategy would help to launch the retarded students on its successful use (e.g., Belmont, Butterfield, and Ferretti 1982). This had to mean that the students possessed the memorizing skills all along but failed to use them.

Subsequent research, extended to more complex abilities such as reading comprehension, confirmed the initial hint that acquiring skills and strategies, no matter how good one became at them, would not make one into a competent reader, writer, problem solver, or thinker. The habit or disposition to use the skills and strategies, and the knowledge of when they applied, needed to be developed as well. Several of the chapters in this yearbook develop this idea, each in the context of a different subject matter.

Palincsar and Brown, considering reading, stress the importance of self-regulation—strategies for clarifying purposes, activating background knowledge, allocating attention to major content, drawing inferences, and the like. Throughout their chapter, they emphasize that all of these strategies are work intensive and that motivation for effortful activity must be viewed as an integral part of instruction in skills for reading. Schoenfeld, discussing problem solving in mathematics, reiterates this theme. He describes a number of specific problem-solving strategies (not the same ones that are relevant for reading) that must be acquired. But he also emphasizes that an important aspect of the teacher's job is to help children accept challenge, to build a classroom where tackling the unfamiliar is not too threatening, and to help children want to solve mathematical problems despite the effort and, perhaps, the difficulties involved. Larkin and Chabay stress the importance of motivation for learning science—motivation intrinsic to the content of instruction rather than rewards or punishments external to it.

That a focus on motivation pervades the writings of a group of cognitive researchers signals an important shift in conceptions of learning and thinking. For many decades, research on motivation has been conducted separately from research on learning or cognition. In psychology, motivation was the domain of social psychologists, who were largely disinterested in what was learned; they cared only about how much effort or attention was expended on some task. Learning and thinking were studied by experimental or cognitive psychologists, who tended to think of motivation as a necessary motor for starting and maintaining mental activity, but not as directly implicated in thinking itself.

Those separatist views are beginning to disappear. Alongside students of cognition who consider motivation an integral part of their concern are social psychologists who now view cognitive processes as integral to motivation. For example, Dweck and Elliott are social psychologists who analyzed students' motivation in study and testing situations (1983). They found that motivation was intimately related to students' conceptions of intelligence. According to Dweck and Elliott, if students think of intelligence as an entity, something fixed that you either have or do not, they are motivated to demonstrate their intelligence by correct performances or, at the worst, to hide the fact that they lack intelligence by not engaging in incorrect performances. But if students think of intelligence as incremental, something that is developed through use over time, they are motivated to accept or even to find challenges, which they think of as occasions for developing their intelligence. Such students, when faced with an initial difficulty, attempt to reformulate the problem, to find elements that they can manage, and to use what they already know to find a solution. These kinds of activities, as this yearbook makes clear, are the very stuff of thinking and problem solving as defined by cognitive researchers.

Shaping Dispositions for Thinking: The Role of Social Communities

The redefinition of cognition to include motivation points to another important aspect of ideas about how thinking skills can be taught. Lauren Resnick's recent review of programs designed to teach higher-order cognitive abilities (1987) noted that most successful programs prescribe cooperative problem solving and meaning-construction activities. This was remarkable because the designers of these programs had mostly begun with purely individual definitions of what they were trying to teach, and had arrived at the need for social interaction more through pedagogical trial and error than through theoretical analysis. Why this discovery? What role might social participation play in developing thinking abilities?

An obvious possibility is that the social setting provides occasions for modeling effective thinking strategies. Skilled thinkers (often the instructor, but sometimes more advanced fellow students) can demonstrate desirable ways of attacking problems, analyzing texts, or constructing arguments. This process—discussed in this volume by Palincsar and Brown, Schoenfeld, and Minstrell—opens normally hidden mental activities to students' inspection. Another possibility is that students can scaffold complicated performances for each other. Each one does part of the task and, by working cooperatively, students can arrive at solutions that one student could not manage alone. In addition, mutual criticism during shared work can help refine individuals' knowledge or skill.

But most important of all, the social setting may let students know that all the elements of critical thought—interpretation, questioning, trying possibilities, demanding rational justifications—are socially valued. The social setting may help to shape a disposition to engage in thinking. There is not much research on how intellectual dispositions are socialized, but we do know how other traits such as aggressiveness, independence, or gender identification develop. By analogy with these traits, we can expect intellectual dispositions to arise from long-term participation in social communities that establish expectations for certain kinds of behavior. Through participation in communities, students would come to expect thinking all the time, to view themselves as able, even obligated, to engage in critical analysis and problem solving. Here, then, is another argument for basic skill and subject matter to be taught as occasions for thought, elaboration, and interpretation throughout school. It is a likely way, perhaps the only likely way, to shape dispositions for thinking.

Cognitive Apprenticeship: A New Challenge

The idea of shaping dispositions to learning points to another theme of recent cognitive research: the power of learning through apprenticeship. School as the institution entrusted with teaching most of what children are expected to learn is a relatively recent phenomenon. Only during the 19th century did the idea arise that it might be appropriate for all children to attend school, at least for a while. And not until well into the 20th century did we come to believe that everyone ought to stay in school through adolescence or that school could take primary responsibility for preparing children for life. In previous generations, people were expected to do most of their learning in the settings where they would practice their skills: in families or in apprenticeships. Despite important limitations, traditional apprenticeships had certain advantages over schools. Most important, because learning took place in the context of actual work, there was no problem of how to apply abstract abilities, no problem of connecting theoretical studies to practical activities, and no temptation to substitute talk about skills for experience in actually using them.

New conditions of work and the much greater value we place today on intellectual competencies for everyone make traditional apprenticeship no longer such a useful form of education; yet it seems possible to bring into school many of the features that made traditional apprenticeships so effective. Collins, Brown, and Newman (in press) have suggested that schools might organize cognitive apprenticeships; that is, they could seek ways to let students participate in disciplined and productive mental work, just as they once participated in craft activities. There is a profound insight to be found here, one that turns our attention away from the traditional educator's problem of how to construct lessons that teach specific skills or knowledge to the new problem of how to create cognitive work environments that are capable of providing true apprenticeship experiences to young students. What would it take to create cognitive apprenticeships in school?

First, cognitive apprenticeship requires a real task—writing an essay for an interested audience, not just for the teacher who will give a grade, reading a text that takes some work to understand, exploring a physical phenomenon that is inadequately explained by a current concept, or solving a mathematics problem that resists initial attempts at solution.

Second, cognitive apprenticeship involves contextualized practice of tasks, not exercises on component skills that have been lifted out of the contexts in which they are to be used. In traditional apprenticeships, novices produce less complex objects than they will when they are more skilled, but they spend very little time practicing discrete skills. In school, cognitive apprentices might work more on writing shorter essays or reading shorter texts than they will later, but they would not spend much time on English usage drills or finding synonyms and antonyms. Similarly, they would not do exercises on separating facts from opinions, but they would take on tasks of analyzing arguments on particular topics or participating in debates, both of which might engage them in a contextualized version of figuring out reliable information in a communication.

Third, cognitive apprentices need plenty of opportunity to observe others doing the kind of work they are expected to learn to do. This observation gives them standards of effective performance against which they can judge their own efforts. When the work to be done is cognitive rather than manual, special attention must be paid to making mental activities overt. In this volume, Schoenfeld's chapter describes how the usually hidden activities of problem solving can be made visible in a mathematics classroom. Hull describes similar processes of making mental activity apparent for writing. Each of the other authors also provides examples of how the actual work of thinking can be made overt for purposes of cognitive apprenticeship.

Introduction to the Chapters

The themes we have outlined here—the centrality of knowledge in learning, the close link between skill and content that it enjoins, the indivisibility of cognition and motivation, the need to shape dispositions for thinking, and the concept of cognitive apprenticeship—are all developed throughout this book. The chapters are organized around core parts of the established school curriculum. Taken together, they point to ways to begin to make the Thinking Curriculum a reality by modifying regular subject matter instruction so that it stresses generative thinking activity throughout.

We have said that the Thinking Curriculum we envision starts at the very beginning of schooling. Early instruction must begin to build the mental processes that children will use automatically and proficiently when they are competent thinkers. The main focus for children's early education is learning the three Rs, and so the Thinking Curriculum must begin as children receive their elementary instruction in reading, mathematics, and writing. These basic subjects are the focus of Chapters 2 through 6. Two subsequent chapters deal with science instruction, another core subject for schools.[2] The yearbook continues with a general chapter reviewing major themes and suggesting further reading on cognitive research pertinent to the Thinking Curriculum. In the concluding comments, we suggest how the Thinking Curriculum relates to two major issues in educational reform.

Reading and the Thinking Curriculum

In Chapters 2 and 3, the authors explain how cognitive research on reading informs instructional approaches and programs that develop children's thinking processes as they are learning to read. First, Annemarie Palincsar and Ann Brown show how self-regulation abilities can be developed as an integral part of the school's elementary reading program. They treat self-regulation as essential to thinking, recognizing that we generally do not consider an individual to be thinking when someone else "calls the plays" at every step. Palincsar

[2] To cover completely the main subjects of the current academic core, one or more chapters on history and other disciplines that form the social studies should have been included. At the time we were planning the yearbook, however, there were no well-advanced programs of cognitive research and instructional experimentation in the social sciences to consult. Readers interested in considering Thinking Curriculum approaches to the social sciences might want to read recent articles by Beck, McKeown, and Gromoll (in press), Newmann (1988), or Voss (1986).

and Brown describe three types of knowledge that self-regulated learners possess: knowledge of learning strategies, metacognitive knowledge, and background knowledge. Successful learners use this knowledge flexibly in accomplishing any learning task, including learning to read. Moreover, the self-regulated learner is motivated to use the three kinds of knowledge and to expend as much effort as needed to accomplish learning tasks. Palincsar and Brown describe studies that examine how the knowledge differences they find among children are related to good and poor performance in reading.

Influenced by the research findings, Palincsar and Brown go on to describe their new vision of reading instruction and provide many practical suggestions for teaching. Their principal goals for instruction are to teach children strategies for accomplishing reading tasks efficiently, to teach them how to monitor and evaluate their own reading activity, and to foster students' motivation to engage in self-regulated reading. They discuss a number of instructional procedures that can help students move toward these goals. They conclude by describing three different approaches to strategy instruction in reading. Although these approaches differ in some important details, each exemplifies the theme of establishing a supportive social community to shape students' dispositions for thinking, and each represents a form of cognitive apprenticeship.

Isabel Beck, in Chapter 3, describes an array of reasoning and problem-solving processes needed to read: identifying words, formulating meaningful units, creating hypotheses, testing hypotheses, selecting a data sample, interpreting data, and evaluating hypotheses in the light of evidence. Her chapter is concerned particularly with children's development of automaticity or efficiency in word recognition, the importance of understanding text structure, and the profound influence of background knowledge on text comprehension. In each of the three main sections of her chapter, Beck discusses recent research and describes specific instructional procedures that have been informed by research findings. She explains how research on word recognition efficiency helps us understand why readers must be able to recognize words effortlessly and suggests instructional procedures that target development of this ability. She also describes research on how a text's organization influences what the reader understands and remembers and suggests how to improve textbooks and reading lessons on the basis of this research. Finally, Beck offers a direct illustration of the centrality of knowledge in cognitive conceptions of thinking and learning. She discusses the great influence that a reader's knowledge about the topic of a text has on comprehension and suggests how comprehension can be improved by implementing instruction procedures that effectively increase students' relevant knowledge.

Mathematics and the Thinking Curriculum

Mathematics also receives a large share of children's attention throughout school. When mathematics is taught in a context of reasoning and problem solving, it too becomes part of the Thinking Curriculum from the very beginning of schooling. The authors of Chapters 4 and 5 discuss ways of teaching mathematics, even beginning arithmetic concepts and skills, in contexts that engage students' thinking and help them generate genuine mathematics knowledge themselves.

Rochelle Kaplan, Takashi Yamamoto, and Herbert Ginsburg make the case in Chapter 4 for teaching arithmetic concepts generatively. They believe that "learning mathematics . . . is not just acquiring behaviors; it is learning to think." As researchers and teachers working in the cognitive perspective, they are well aware of the centrality of knowledge in thinking, the use of prior knowledge in learning, and the restructuring of knowledge. Since they are focusing on children's learning of arithmetic concepts and skills, the prior knowledge of interest to them is the informal mathematical knowledge developed outside school that children bring to instruction. Children use this informal knowledge to invent personal procedures to deal with the formal arithmetic material they confront in school. These invented procedures can deal effectively with most problems children encounter. But sometimes, most often when trying to learn a school arithmetic procedure, children invent procedures that are systematically defective (or "buggy"), so that a child makes the same kind of error again and again. Kaplan, Yamamoto, and Ginsburg regard such errors as clues to understanding children's thinking processes. They point out that children's mathematics learning is also influenced by what the children believe about the nature of mathematics and about what teachers expect of them.

Putting all these considerations together, Kaplan, Yamamoto, and Ginsburg suggest that the goal of mathematics instruction should be to help children interpret the formal concepts and procedures of the mathematics curriculum in terms of their informal knowledge, invented procedures, and beliefs. The three extended examples comprising the remainder of Chapter 4 demonstrate how such an instructional agenda can be carried out. The examples chosen are learning number facts through exercises in discovering patterns and relationships in the multiplication table, developing mental arithmetic strategies as a precursor to written algorithms, and using manipulatives to expand children's arithmetic conceptualizations. In these examples, Kaplan, Yamamoto, and Ginsburg illustrate not only the theme of teaching concepts generatively in a problem-solving context, but also the theme of setting up discussions in a social community to help shape students' dispositions for thinking.

A parallel set of ideas is developed in Chapter 5 by Alan Schoenfeld, but his proposals go well beyond the early years of schooling. Schoenfeld argues that, with the availability of low-cost, portable, and powerful calculators, it is no longer appropriate to emphasize number and symbol manipulation in the mathematics curriculum, and that problem solving should become a main focus of instruction in mathematics at all school levels. In the chapter's longest section, Schoenfeld defines and illustrates problem-solving strategies and discusses the kinds of classroom situations conducive to students' development of these strategies. In another section, he discusses metacognition and self-regulation in connection with mathematical problem solving. Lastly, he describes what it means to develop a "mathematical point of view," again in the framework of solving mathematical problems. In the course of the chapter, Schoenfeld's comments reflect at least four of the book's organizing themes of cognitive instructional theory—the integration of skill and content in learning and thinking, the integration of cognition and motivation, the role of social communities, and the principles of cognitive apprenticeship.

Writing and the Thinking Curriculum

Writing also accounts for a large share of students' instructional time in school. In many schools, teachers customarily allot the bulk of this time to a variety of skill development exercises, since it is widely believed that students' success depends on mastering separate skills. The emphasis on isolated writing skill components has been common in American schools, largely because the curriculum is grounded in a behavioristic psychology of learning that espouses hierarchies of separate skills. Hull's chapter, however, provides a new perspective on writing that can liberate teachers from the isolated skill-development emphasis. It is a perspective that is now spreading into an increasing number of writing classrooms.

Hull begins by explaining how writing research in the past two decades has redefined what writing is like and which students will be able to write. We now understand writing as a complex cognitive process embedded in a social context. Writing is more than a stringing together of separate skills; it is an activity in which various cognitive processes—planning, transcribing text, and rewriting—happen recursively and in no particular order. Hull views writing as a problem-solving activity involving the individual in complex cognitive and linguistic processes such as organizing, structuring, and revising. Expert writers give more attention to some of these processes than novice writers, and beginning students generally have incomplete or flawed representations of what writing entails. Many fail to recognize that writing is a problem-solving activity that takes place over time and that writing is socially constructed. Hull's interpretation of writing as a social construction implies that educators must not only provide instruction on the processes of writing but also provide opportunities to practice it in all of its open-ended complexity and to become enculturated into a "discourse community."

Following her account of recent writing research and its implications, Hull describes a basic English instruction program that exemplifies key features of the new pedagogy. This leads to a discussion of three key maxims for writing instruction. First, learning to write requires tasks that are authentic, tasks that are real instances of communication. Students become engaged not in skill-development exercises that are merely ends in themselves, but in extended, purposeful, problem-solving activity—in other words, in writing apprenticeships. Second, student writers can acquire new knowledge and skills through scaffolding, which is provided through social interaction. The social group's support encourages writers to stretch beyond their current capacity and to negotiate the next stage of writing development successfully. The group's scaffolding also encourages refinements in its members' thinking processes. The last maxim is to recognize that a writer's performance has a history and a logic. This gives the teacher both a way to understand and investigate students' difficulties with writing and a means to identify appropriate instruction for particular students.

Science and the Thinking Curriculum

While Chapters 2 through 6 focus on the three Rs, the Thinking Curriculum we envision is hardly confined to them. Most educators have long associated science instruction with inquiry processes and problem solving, key signs of the Thinking Curriculum. The very same signs characterize much good instruction in social studies, history, geography, art, health, computer science, and other school subjects, both academic and vocational. For this reason, what the authors of Chapters 7 and 8 tell us about the contributions science teaching makes to the Thinking Curriculum should not be interpreted as applying to science alone. Instead, these science chapters represent the many other subjects in elementary and secondary schools where the Thinking Curriculum can be fostered.

James Minstrell, author of Chapter 7, is a high school science teacher who also conducts cognitive research. He looks at cognitive research from the practical perspective of how it can inform his teaching and help his students learn science more effectively. Consistent with this perspective, he tells us about teaching science for understanding using richly annotated, step-by-step accounts of a physics teacher interacting with his students in their classroom. Minstrell's annotations call attention to the ideas from cognitive research illustrated in the classroom interaction, to the students' conceptual struggles in coming to grips with accepted scientific notions, and to the instructional strategies the teacher employs. In the chapter's conclusion, Minstrell reflects on the general principles drawn from cognitive research that impact science instruction, and he offers a number of guidelines for designing instructional environments that encourage the development of students' reasoning skills and understanding in science.

Jill Larkin and Ruth Chabay take us in Chapter 8 to another environment for promoting thinking in science—a world built around students' interactions with microcomputers. Larkin and Chabay's ideas represent the unique possibilities for fostering thinking with microcomputer-based instruction, not only in science, but in virtually any subject matter. The chapter begins with a discussion of some of the recent research on the mechanisms of scientific thinking: how these mechanisms are learned and what motivates students to learn. They illustrate what researchers have found about how the problem-solving behaviors of experts in physical science contrast with students' behaviors. Experts spend most of their problem-solving time reasoning qualitatively about forces, momentums, velocity changes, and other concepts and about the relations between them. They write down equations and substitute values in them only occasionally. By contrast, students spend almost all their time trying to remember equations suitable for the problem, manipulating equations to obtain expressions for desired quantities, and substituting values into the equations to get numerical results. Larkin and Chabay ascribe these contrasting behaviors to differences in the knowledge that beginners and experts possess. They differ both in their knowledge of science concepts (students' knowledge is limited to everyday and often imprecise conceptualizations) and in their knowledge of problem-solving procedures (experts' procedures are infused with more knowledge of the discipline's generative concepts).

Larkin and Chabay also discuss research on students' motivation, calling attention to three principal motivating factors: challenge, curiosity, and control. They describe how these factors influence six features of successful instruction that they identified in recent instructional research. Larkin and Chabay clearly illustrate the theme that the Thinking Curriculum must attend simultaneously to cognitive and motivational aspects of thinking. The chapter concludes with discussions of four examples of microcomputer software designed to teach thinking in science. These discussions illustrate their six features of good instruction and provide guidance for educators in selecting effective microcomputer-based instructional materials.

A Further Look at Cognitive Research

Following the two science chapters, the discussion turns from considerations of the Thinking Curriculum in specific school subject matters to a reprise on general themes of cognitive research. In Chapter 9, John Bransford and Nancy Vye offer their perspective on current cognitive research and its instructional implications. They organize their chapter around three areas of research that inform current cognitive theories of instruction. The first part focuses on attempts to understand the nature of expert or competent performance. The second describes research on the initial state of learners before instruction begins, research that seeks to find out how well students' skills and preconceptions match the subject-matter concepts and abilities that are the goals of instruction. The third section deals with the transition from the students' initial knowledge state to a more expert competence. Bransford and Vye echo the views of other cognitive researchers when they propose that the optimal conditions for learning involve students' intense engagement in reasoning, elaboration, and problem-solving activities.

Bransford and Vye's chapter contains many suggestions for further exploration of the possibilities of the Thinking Curriculum. You will find in its well-structured discussions numerous ideas and illustrations that can stimulate your inventiveness in devising ways to enhance students' thinking skills. Bransford and Vye have related their general discussion to specific subject-matter learning, partly through many cross-references to the seven subject-matter chapters in this yearbook. In addition, they have included a rich bibliography with their chapter to enable further pursuit of these ideas.

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2
Instruction for Self-Regulated Reading

Annemarie Sullivan Palincsar
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Several regions of the country boast of a "mystery spot" where visitors can experience water that appears to flow uphill, floors that seem to move, and rooms that feel as though they are becoming smaller even though they never really change in size. For some, the cognitive dissonance created by these phenomena make the mystery spot a fun and challenging place to be. For others, the mystery spot is less intriguing and may be unsettling and aversive.

In some respects, classrooms are like "mystery spots," with the same potential for amusement and intrigue or disquiet and confusion. Students' responses to the mysteries of classroom activity reflect, in part, their awareness of the variables that are important to learning and their ability to take control of their learning environment. This ability is often referred to as "self-regulated learning."

In this chapter, we focus on ways to provide students, especially those who have difficulty learning from text, with knowledge of the variables that are important to reading comprehension and knowledge of strategies that facilitate this comprehension and lead to self-regulation of reading activity.

What Does It Mean To Be a Self-Regulated Learner?

Self-regulated learners are able to use three main types of knowledge in a flexible manner: (1) knowledge of strategies for accomplishing learning tasks efficiently, (2) metacognitive knowledge, and (3) real-world knowledge (Brown, Campione, and Day 1981, Pressley, Borkowski, and Schneider 1987).

Speculation abounds as to the number of strategies useful for understanding text and the relative power of one strategy compared to another. However, in a review of theoretical treatments of reading comprehension, only six strategies were found that both monitor and foster comprehension:

(1) clarifying the purposes of reading to determine the appropriate approach to the reading activity (e.g., skimming, studying);

(2) activating background knowledge to create links between what is known and the new information presented in the text;

(3) allocating attention so that the major content, not trivia, becomes the focus;

(4) evaluating content critically for internal consistency and compatibility with prior knowledge and common sense;

(5) using monitoring activities (e.g., paraphrasing, self-questioning) to determine if comprehension is occurring;

(6) drawing various kinds of inferences (e.g., interpretations, predictions) and testing them (Brown, Palincsar, and Armbruster 1984).

This list, as well as observations of the activities of skillful readers, suggests that most likely there is only a small number of strategies that teachers might target for instruction. The relative merits of one strategy over another continue to be debated and researched, but it is worth noting that only a few strategies have received rigorous attention. These strategies include question generating, summarizing, and imaging (Palincsar and Winn in press, Pressley, Goodchild, Fleet, Zachjowski, and Evans in press).

The success of self-regulatory activity is, in large measure, a reflection of what we know of our own learner characteristics and the task demands. This type of knowledge is often called metacognition. Metacognitive knowledge enables the reader to select, employ, monitor, and evaluate the use of strategies. To illustrate the nature of strategy knowledge, consider the following two students who demonstrate very different approaches to the same learning task.

Ben and Gary are preparing for an essay test on a chapter presenting the effects of environmental pollution on the ecosystem.

Since essay tests are hard for him, Ben is disappointed that the teacher has chosen to use that format. Ben's reaction reflects his knowledge of himself as a learner. He decides that he will prepare for the test by outlining the information in the chapter and organizing it so it is manageable to study and recall. While skimming the chapter, he notices that the authors have presented the information by linking causes and effects. Ben draws a line down a piece of paper, titles one column "causes" and the second "effects," and proceeds to record the information. Ben's knowledge of himself and strategies (using text structure to outline the chapter) interact to influence his study plan. Having completed this outline, Ben lays it aside and self-tests his recall by drawing a diagram of the chapter illustrating the relationships between events and outcomes in the ecosystem. In this manner, Ben takes control of his learning activity.

Gary is also unhappy about the essay format because he knows he does better on multiple-choice tests. He too demonstrates knowledge of himself as a learner. Since he did so well on the last multiple-choice test, Gary decides to study for this test in the same manner. Unfortunately, in making this decision, Gary has ignored the demands of the task. He searches for each word in dark print in the text and writes out the definition of that term. In this instance, Gary's failure to consider the task demands, perhaps in hand with a limited repertoire of study strategies, leads him to select a less-effective strategy.

The contrast between Gary and Ben illustrates how metacognitive knowledge affects the selection and deployment of strategies to facilitate desired learning outcomes. But the vignette of Ben and Gary does not address a third type of knowledge—background knowledge.

Clearly, having appropriate knowledge of a topic aids understanding of the text. For example, if Gary were a young member of Greenpeace who had exhibited considerable interest in environmental issues, his background knowledge might compensate for his apparently ineffective study strategy. However, partial or incomplete knowledge of a topic can impair comprehension (Alvermann, Smith, and Readance 1985). For example, Alvermann and colleagues observed that students who were induced to activate background knowledge regarding sunlight, a topic about which they had many misconceptions, permitted this previous knowledge to override information in the text that was incompatible with what they knew. Consequently, these students performed poorly on tests of written recall and comprehension when compared with students who were not induced to activate background knowledge. This observation demonstrates the role that comprehension monitoring assumes in self-regulated reading activity.

Anyone reading the preceding vignette might have been struck by how "effortful" Ben's studying behavior was in contrast to Gary's and may wonder whether the relevant issue is motivation rather than metacognition. This is a trenchant observation, for, in addition to possessing self-knowledge, the self-regulated learner demonstrates the motivation to employ that knowledge effectively. Recent research examining the relationship between self-regulation and motivation portrays a complex picture in which students' performance reflects: (1) the values they attach to the task and the learning activity, (2) their feelings of self-competence regarding the task, and (3) their perception of certain factors, such as luck and effort, to which they attribute their performance on a task. Furthermore, this picture changes with age and ability. While comprehension strategies are critical in predicting the success of younger students and poorer readers, awareness and attitudes toward reading better correlate with reading achievement for older students and better readers (Paris and Oka 1986).

In summary, effective learners regulate their learning activity by managing, monitoring, and evaluating. In addition, they are motivated to assume responsibility for their learning. The question then for teachers is how to acquire knowledge about their students' self-regulatory activity.

Determining Students' Metacognitive and Strategic Knowledge

At one time or another, most teachers have expressed the fervent desire to "climb inside" students' heads to figure out what's going on in there (and, in so doing, be assured that something is indeed going on). One obvious way of ascertaining what children know about the demands of reading and about themselves as readers is to ask them questions. For example, we might show a child a textbook and ask, "What do you do when you want to be sure to understand and remember a chapter from this textbook so that you could pass a true/false test? Why is reading a book such as this sometimes difficult? What can you do if you are having difficulty understanding a book such as this?" The more specific the questions and the more specifically the context is defined for the child, the more useful the information an interview yields (Garner 1987).

What types of differences among students emerge in such interviews? Consider the interview study conducted by Myers and Paris (1978) with 2nd and 6th grade children. While the young readers identified the goal of reading as "sounding out the words correctly," the older children generally identified the goal as figuring out the meaning of the text. In addition to this conceptual difference, younger children displayed less knowledge about text features (e.g., the functional importance of first and last sentences in paragraphs); reading strategies (e.g., rereading can be a useful means of fixing up a comprehension problem); and criterial tasks (e.g., the most effective way of retelling a story is to identify the gist of the material). Investigations such as this suggest that teachers can anticipate differences in the metacognitive and strategy knowledge of children as a function of age and school experience. However, age alone doesn't determine students' knowledge of the demands of reading. Forrest and Waller (1980) studied the relationship between children's knowledge of reading and their levels of achievement with reading tasks by interviewing children at three reading levels in grades 3 and 6. They observed both developmental and ability differences, and the older and more successful readers in both grades indicated (1) greater awareness of the "meaningful" nature of reading, (2) better appreciation of the importance of using self-testing activities while reading, and (3) stronger recognition of the need to deploy strategies differentially depending on their purpose for reading.

While there is, of course, a considerable leap between what children report they do and their actual activity while reading, interviews are a useful means of gaining partial access to the child's knowledge and attitudes. In addition, interviews are a useful way of engaging students in dialogue about themselves as readers and the demands of different reading situations.

A 1st grade teacher, for instance, asked her principally at-risk students, "What would you do if I told you that I was going to read a story and ask you some questions about the story when it was over?" Even in this small group of six students, there was a rich array of responses. One child suggested that she would "keep my hands on the desk and my feet on the floor" while another said he would "turn on the tape recorder in my head." This prompted a third child to suggest that he would "check to be sure my listening ears are open." A fourth child volunteered that he made pictures in his head as he listened. The teacher discussed how paying attention (as suggested by at least two of the children's responses) was indeed an important part of understanding and remembering, but that sometimes it is not enough just to pay attention; it is necessary to think about the information that you're hearing. She then referred to the example of making a picture in your head to help you remember. She used this discussion as a springboard for introducing the children to the fact that they were going to learn some strategies that would help them think about stories to which they were listening.

In addition to using interviews, researchers use "think aloud" procedures that ask students to share the thoughts they are having as they engage in various reading activities. In these studies, we can discern developmental differences as well as differences between more- and less-capable readers. Protocols from investigations using the "think aloud" procedure (e.g., Bereiter and Bird 1985) reveal information about the students' use of strategies to foster reading, the extent to which they monitor their comprehension, and the measures they take to restore meaning when they have experienced difficulty. Anyone who is interested in using "think aloud" procedures in the classroom should consult Alvermann (1984) for a number of suggestions that will increase the likelihood of gaining useful information in a manner that is nonthreatening to the student.

An alternative to the interview or "think alouds" is to present students with vignettes similar to the one about Ben and Gary, ask them to evaluate the approaches each student took, and ask them to compare each to their own approaches to comprehension activities.

Researchers have also investigated differences in specific strategy use to understand self-regulated learning among children of various ages and reading abilities. We will discuss investigations of rereading and summarizing strategies to clarify the differences between children who self-regulate and those who do not. We will use this discussion to indicate how teachers could identify an instructional agenda for teaching students to engage in self-regulation.

Typical of the research examining students' rereading portions of the text is the work of Garner and her colleagues. They presented students with narratives accompanied by questions, some of which required looking back in the text to locate information. The investigators report that more successful readers differentiated between situations requiring lookbacks and followed through on the use of text reinspection with greater reliability than did less successful readers (Garner and Reis 1981). The activity of the more successful readers indicated that they were more aware of text as a source of information, recognized the kinds of questions that needed to be answered by looking back in the text, and were more accurate in knowing the place they should return to in the text.

Good and poor readers also demonstrate differences in summarization tasks. The important skills incorporated in summarizing make it a particularly useful means of ascertaining differences among readers. To successfully summarize, the reader must be able to (1) judge the relative importance of ideas in the text, (2) condense the information, and (3) organize the information. Age and ability differences have been discerned in students' ability with each component.

For example, age-related differences in the ability to evaluate the relative importance of ideas in a text were detected in a study conducted by Brown, Smiley, and Lawton (1978). Third, 5th, and 7th graders, as well as college students, were given texts that presented a story with one idea written on each line. The students were asked to rate each idea on a four-point scale ranging from least to most important. Their ratings were then compared with those of English teachers who had done the same activity. The ratings of students below 7th grade did not reliably distinguish among the four levels of importance.

Brown and Day (1983) investigated the ability of students in grades 5, 7, and 10 to condense text. The students first were asked to read and take notes on passages of about 450 words, and then they were asked to generate 60-word summaries. Students of all ages were generally able to delete from their final summaries repetitive or trivial information. However, the ability to identify the main idea, whether by recognizing a main idea sentence or by inventing one, improved across grade levels. Only the college students consistently were able to invent main-idea sentences, although they invented them only half of the time when it would have been appropriate.

Finally, we turn to the last component in summarizing: organizing information. Meyer, Brandt, and Bluth (1980) conducted a study investigating the ability of 9th graders to organize and recall information they read. The 9th graders were given texts that were organized with clear structures (e.g., comparison, problem/solution). After they studied the text, the students were asked to recall, in writing, all they could remember from the reading. Their papers were scored, not only to determine the amount they were able to retain, but also to determine the extent to which they used the text structures to organize their recall. The results indicated that, overall, less than half the 9th graders used the organization of the text to aid their recall. The students who did use the organizational structures were those identified as good readers by reading achievement tests. The majority of poor readers did not use the organizational structure.

While this is an interesting outcome in itself, it is also important to note that students who did use the organizational structure of the text were able to recall much more of the text than those who did not.

To summarize what we've discussed thus far: There are differences among students on an array of factors that influence the ability to self-regulate reading activity. These differences are reflected in (1) the knowledge that students possess about the demands of reading, (2) their evaluations of the appropriateness of various approaches to reading, (3) how they self-monitor their comprehension of text, and (4) how they actually engage in reading activity. We can observe these differences when comparing children across various ages, suggesting that the acquisition of the knowledge and behaviors are, in part, a function of experience. However, there are also differences when comparing good and poor readers of the same age. In addition to possessing more knowledge, self-regulated readers are motivated to use this knowledge to take control of their learning. The emerging picture of the relationship between these types of knowledge and reading achievement have instructional implications that have begun to influence the way we conceptualize reading instruction.

Instructing Students to Become Self-Regulated Readers

Literacy learning is not only a cognitive process; it is also a social and linguistic process. Children learn to read and write becau hey recognize the functions that reading and writing serve. We cannot control children's incentive to read, but we can certainly facilitate opportunities to participate in literacy events. It is important to build bridges between the contexts of literacy in the home/community and the classroom/school. A program in Hawaii (Au 1979) offers an excellent example of instruction that cultivates the acquisition of reading in an environment that acknowledges the cultural and experiential heterogeneity of students. Also important are the data indicating that time spent reading is the best single predictor of reading achievement (Anderson, Wilson, and Fielding 1988). The desire for literacy and the benefits of literacy need to be modeled for children in the same fashion as cognitive activity. Cognitive instruction does not supplant the social and linguistic goals associated with literacy learning; rather, it takes place within a context that reflects these aims.

Given this characterization of the self-regulated reader, the complementary goals of instruction become (1) teaching students the strategies for accomplishing reading tasks efficiently, (2) teaching students to monitor and evaluate their own reading activity, considering the demands of the reading tasks, their strengths and weaknesses as learners, and their background knowledge relevant to the text, and (3) fostering the motivation to engage in self-regulated reading.

Selecting Strategies for Instruction

Anyone familiar with the school day already knows there is too much to teach in too little time. Thus, determining the place of strategy instruction in the curriculum is not a trivial issue. For the majority of teachers, teaching for self-regulation is probably less a matter of choosing different things to teach than it is selecting different approaches to teaching for the same objectives. While working on these objectives, teachers have instructional opportunities to teach self-regulation before, during, and after reading text (Palincsar, Jones, Ogle, and Carr 1986).

Instruction Prior to Reading Text. Teachers traditionally offer some form of instruction before asking students to read text. Quite often, this takes the form of presenting the new, difficult, or technical vocabulary that students will encounter. Instructional research (Schwartz and Raphael 1985) has focused on how we can teach students procedures to acquire new concepts and vocabulary in a manner that promotes their self-regulation of this knowledge. Fourth and 5th graders were taught to conceptualize a definition as answering these three questions: (1) what is it? (2) what is it like? and (3) what are some examples? The students were then taught how to use background knowledge and other sources (e.g., dictionaries and textbooks) to locate and organize the components of a definition. In addition to learning how to write definitions, the students were taught to use the components of a definition to monitor and evaluate their work. This instruction proved to be a very effective means of increasing students' ability to independently acquire vocabulary and concepts.

In addition to vocabulary instruction, teachers typically spend time before students read in the "motivation phase" of the lesson. The teacher attempts to set the purpose for reading in a number of ways. For example, the teacher may provide an overview of the test, outline a series of questions the students should be able to answer after they read, or set a very general purpose for reading (e.g., "Read to see how Mandy deals with the unreasonable demands she feels her parents are making of her").

There is nothing wrong with any of these techniques. However, they fall far short of teaching students how to self-regulate, and they may unwittingly limit the students' involvement in the reading activity. They are also fairly artificial means of "motivating" students to read. They do not match well with the demands of everyday reading.

Recall that successful readers clarify the purposes for reading, activate background knowledge, and assess the match between the content of the text and prior knowledge. The teacher-directed nature of the activities outlined above usurps the students' power to determine the reason for reading, which should influence their approach. Let's contrast these activities with instruction to teach students to prepare independently for reading.

Investigators have looked at several instructional approaches for prereading activities that promote student engagement in activating background knowledge and purpose setting (Langer 1984, Ogle 1986). In each approach, the teacher identifies the topic of the text, and the students are encouraged to "brainstorm" what they already know about this topic or what they would like to know. Students generate a series of questions and as they read, they monitor the relationship between what they discussed before their reading and what they are encountering in the text. They then determine which of their questions have been answered in the text.

Increasing students' awareness of text structure, or the way the ideas in a text are interrelated to convey a message to the reader (Meyer and Rice 1984), has also proven to be an effective prereading activity. We rarely leave for a place we've never been before without consulting a map or obtaining directions. In the same way that a map helps travelers organize their journey and monitor their progress, the structure of the text can help students organize and retain the information they are reading and monitor their understanding and recall of this information.

Fitzgerald and Spiegel (1983) taught low-achieving 4th grade students the features typical of narrative text (e.g., setting, goal, attempt, and outcome). They also taught the students the relationship among these story features and the relationship between knowledge of these parts of the story and comprehension of the story. Instruction on story features enhanced not only the story structure knowledge but also comprehension and recall of stories.

Instruction of Strategies During Reading. Appropriate prereading instruction is aimed at clarifying the purposes of reading, activating background knowledge, and inducing students to use the structure of the text to guide their reading. While reading text, the successful reader allocates attention to the major content; monitors the extent to which comprehension is occurring, is internally consistent, and is compatible with prior knowledge; and makes and tests inferences. Students can be induced to engage in these activities in numerous ways. Historically, teachers have used advance organizers, provided an overview of the content, or posed questions that call the reader's attention to particular information in the text.

Complementing these teacher-led activities is instruction in strategies that students can use to control their own activity during reading, including increasing their interaction with the text and monitoring their comprehension.

The many important skills necessary for successful summarization suggest its usefulness as a reading-to-learn strategy. Studies investigating the instruction of summarization (Day 1986, Hare and Borchardt 1984) have focused on teaching students to use the following basic rules.

1. Select topic sentences where available.
2. Invent topic sentences where they are not provided.
3. Use superordinate terms to identify lists.
4. Delete trivial information.
5. Delete redundant information.

The success of summarization instruction appears to be a function of how the instruction is conducted. When students are taught the rules of summarization and are provided practice in integrating and applying these rules, as well as evaluating the effectiveness of rule use, instruction in summarization has improved comprehension and recall of text.

A second strategy is to teach students to generate questions for themselves. To successfully self-question, readers must identify the information in the text and self-test their knowledge of it. Theoretically, this questioning should promote the reader's self-regulation, but the results of instruction in self-questioning have been modest (Wong 1985). For example, Davey and McBride (1986) provided 6th graders with five 40-minute training sessions during which they taught them to (1) focus on the gist of the material, (2) integrate information across the passage, (3) evaluate the questions they had generated, and (4) determine that they could answer their own questions. This instruction was compared with four conditions in which instruction was less complete. For students to improve both their literal and inferential recall of the text, the complete program of instruction was necessary.

A third strategy, whose value we already noted, is calling students' attention to text structure while they read. For example, Short and Ryan (1984) taught 4th graders to underline certain clues that would answer five structure-based questions as they read narrative text: (1) Who is the main character? (2) Where and when did the story take place? (3) What did the main character do? (4) How did the story end? and (5) How did the main character feel?

The students were taught how to identify these clues, how to ask questions about what was coming up in the story based on these clues, and to make predictions based on their own experiences. In addition to investigating the usefulness of this instruction, Short and Ryan were interested in the effects of "attribution training," or teaching students the relationship between effort and outcome.

Attribution training took the form of five statements the students were to verbalize to themselves: (1) Enjoy the story. (2) Praise yourself for a job well done. (3) Try hard. (4) Just think how happy you will be when it comes time for a test and you're doing well. (5) Give yourself a pat on the back.

Short and Ryan found that those students who received instruction in the strategy did better on measures of recall and could take better notes on a narrative story than did students who received attribution training only. Moreover, attribution training given together with strategy instruction only minimally augmented the results that were obtained with strategy instruction alone.

Attending to text structure has also been taught as a strategy to be used while reading expository text. Students can be taught to see the text's hierarchical organization (i.e., the headings and subheadings) or conventional text structures (e.g., compare/contrast, problem/solution, cause/effect) to aid their study. In one investigation, Armbruster, Anderson, and Ostertag (1987) systematically taught 5th graders to recognize and use the problem/solution pattern, while another group of students read the same materials and answered related questions. The students who received the text structure instruction performed better than the control students on both an essay question and a summarization task.

Instruction for Self-Regulation after Reading. Most teachers use questioning during the "after reading" phase of instruction. Typically, the teacher asks the question, but it is possible to increase student involvement and responsibility in this activity. For example, Raphael and McKinney (1983) taught students the relationship between comprehension questions and information sources. They began by teaching students labels for three question types. Text-explicit questions were called "right-there" questions; text-implicit questions were labeled "think-and-search;" and script-implicit questions were referred to as "on-my-own" questions. Next, the students were given various kinds of practice in using these labels. Students who received this instruction more accurately identified question types and gave better answers to questions than did students who only received practice answering the various questions.

Integrating the Before, During, and After Components of Reading. Armbruster and colleagues (1984) have developed an instructional procedure called SPaRCS for integrating the preceding strategies. SPaRCS stands for (1) survey/predict prior to reading, (2) read/construct during reading, and (3) summarize following reading. Students were taught to use graphic outlines during these activities. They first generated the categories of information they predicted they would be reading and displayed them in a table. As they read, the students identified the information for each category in the text and entered it in the table. They then discussed this information and filled in gaps that remained after their reading. Finally, they constructed a summary of the information by discussing and integrating the information from their graphic outlines. The investigators observed that while able readers could independently and reliably use this procedure, students who demonstrated comprehension problems required considerable instruction and guidance in the use of graphic organizers and learned best by first applying them to clearly structured materials.

Determining How to Engage in Strategy Instruction

Virtually all of the instructional research on strategy instruction has certain features in common. These features have been identified with "direct instruction" (Rosenshine 1979) and include (1) identifying the strategy, (2) explaining why it is being taught, (3) demonstrating its use, (4) guiding students' acquisition and application of the strategy, (5) explaining when the strategy should be useful, and (6) informing students how to evaluate the effectiveness of using the strategy and what to do if the strategy has not been effective. But not all approaches to strategy instruction are the same. We illustrate this point by describing three different programs of strategy instruction: Informed Strategies for Learning, Responsive Elaboration, and Reciprocal Teaching.

Informed Strategies for Learning (ISL) is a curriculum developed by Paris, Cross, and Lipson (1984). It consists of 20 modules that address three comprehension processes: constructing text meaning, monitoring comprehension, and identifying meaning. Each module focuses on a different strategy (e.g., finding the main idea).

Each strategy is taught in three lessons, which inform students about the value of the strategy, provide metaphors that will help the children understand the strategy, discuss the strategy, offer guided practice in using the strategy, and apply the strategy across science and social studies content. The research conducted with ISL indicates that the curriculum improves reading awareness and strategy use.

In contrast to the ISL curriculum, Responsive Elaboration can be embedded in the existing curriculum. Duffy, Roehler, Sivan, and others (1987) focused their research on the teaching of skills presented in the basal series adopted by the school district as strategies. Specifically, teachers were shown how to teach their students the mental processes an expert reader would use when strategically applying the skills presented in the text for monitoring and restoring comprehension. The teachers were taught (1) how to recast the isolated skills as problem-solving strategies by analyzing the cognitive and metacognitive components of the skill and (2) how to model these components for their students. The following passage highlights a teacher who is modeling the process of using context clues to ascertain the meaning of a word.

> I want to show you what I do when I come to a word I don't know the meaning of. I'll talk out loud to show you how I figure it out. [Teacher reads.] "The cocoa steamed fragrantly." [Teacher says] Hmm, I've heard that word "fragrantly" before, but I don't really know what it means here. I know one of the words right before it though, "steamed." I watched a pot of boiling water once and there was steam coming from it. The water was so hot, this must have something to do with the cocoa being hot. Okay, the pan of hot cocoa is steaming on the stove. That means steam is coming up and out, but that still doesn't explain what fragrantly means. Let me think again about the hot cocoa on the stove and try to use what I already know about cocoa as a clue. Hot cocoa bubbles, steams, and smells! Hot cocoa smells good! [Teacher rereads.] "The cocoa steamed fragrantly." That means it smelled good! (Duffy and Roehler 1987).

The awareness and use of these strategic approaches to reading resulted in higher achievement scores than those indicated by the control group. These gains were maintained five months following the conclusion of the intervention.

The third approach to strategy instruction, Reciprocal Teaching (Brown and Palincsar in press, Palincsar and Brown 1984, in press), targets the instruction of four strategies. They're taught and practiced as a set of complementary activities to be used flexibly as the text, the needs of the reader, and the demands of the task suggest. In contrast to Responsive Elaboration, Reciprocal Teaching focuses less on teacher explanation and strategies, putting greater emphasis on teachers and students collaborating to bring meaning to the text.

At the heart of Reciprocal Teaching is a dialogue about the meaning of the text. The dialogue is structured with the use of the four strategies that promote comprehension of text and monitoring of comprehension.

The teacher and students take turns leading this dialogue, breaking the text into segments (initially by paragraphs). The discussion is focused on generating questions from the text, summarizing the text, clarifying portions of the text that impaired understanding, and predicting the upcoming content, based on clues that are provided by the content or the structure of the text.

Before beginning the dialogues, a series of five lessons introduces the students to the "language" of Reciprocal Teaching by providing direct instruction in each strategy. This also offers the teacher opportunities to evaluate the students' ability to use each strategy. When the dialogues begin, the teacher assumes principal responsibility for leading and sustaining the discussion. The teacher also can model skilled use of the strategies for understanding the text. However, even from the first day of instruction, the children are encouraged to participate in the dialogues, for example by commenting on the teacher's summary or by suggesting additional predictions. The teacher supports each student's participation by providing specific feedback, additional modeling, explanation, and prompting. To illustrate, the following excerpt is from a dialogue between a 1st grade teacher and a group of six children, five of whom were characterized as at-risk based upon language difficulties. The group is listening to a text about bear cubs.

> [The teacher reads.] "Baby bear was bigger than his sister and he began to play too rough. His sister jumped onto a tree trunk and climbed quickly upward."
>
> Kendra interrupts for a clarification: "What's rough?"
>
> Mara, one of the children, suggests, "Like you say rough texture."
>
> The teacher interjects, "Well, that's one kind of rough."

Another child, Robert, adds, "The other one is like they beat you up."

The teacher turns their attention to the text for clarification. "That's another kind of rough. Let me read the sentence and see which one you think it is. If it's the way you feel the texture, or the beating up." [Rereads.] "Baby bear was bigger than his sister and he began to play too rough."

Mara says, "It's the kind [illegible] means [referring to Robert]."

Teacher replies, "The punching and the hitting, playing too hard. Okay.

[The teacher continues reading and comes to a portion of the text where a prediction would be appropriate.] "His front paws caught hold on the branch, but he could not pull himself up. He hung there, swinging in midair. . . . Now the limb bent lower, and lower, SNAP. . . ." [Teacher stops reading.] "Prediction?"

Children answer, "It fell."

The teacher replies, "That's your prediction. Let's see if it's true." [The teacher reads] "The limb broke and baby bear fell, splash into the cold stream. He squalled for his mother. Now the mother splashed into the water. . . .

Robert interrupts for another clarification, "What's squalled?"

[Teacher rereads] "He squalled for his mother. What do you think he did when he fell into the water?"

Robert answers, "Whining, whining and crying."

Teacher: "Good, Robert!"

The teacher then continued reading and asked the discussion leader, Margo, to begin by asking her question.

Margo asks, "What did he lay in?"

The group has been talking about the different kinds of questions that one can ask: questions that are about details in the story and questions that you have to think about to answer. Perhaps as a consequence of these discussions, Mara offers the following comment on Margo's question: "It's true you could get an answer for that question. But is that gonna get an answer from more than one people? Probably, it's just gonna get an answer from one, and there's better questions you could ask."

The teacher interjects at this point: "Well, let's go ahead and answer her and see if we can get *this* one."

The children then answer Margo's question and she asks another one, "What did the mother do after he squalled? Robert?"

Robert: "Licked him all over."

Margo: "Correct. Any more questions?"

Several children have addition questions which the group discussed.

The teacher then asks Margo to summarize:

Margo: "This part of the story told us about baby bear and sister bear are wrestling."

The teacher provides the following feedback regarding Margo's summary: "Tell us a little bit more. There's an important thing you left out. While they were wrestling, what happened?"

The children then complete the summary as a group, adding additional details about the events which occurred in that part of the story. Included in their summary is the observation that Baby Bear didn't get hurt.

Teacher: "Why didn't he get hurt?"

Kinata: "Water is real soft, like you can jump on it like a mat. If you land on a rock you will hurt yourself."

Teacher: "A rock doesn't give way does it? It just stays hard; but the water will give way and come around you. Good point! We got some good discussion.

Mara: "You know what time of year it was when it told you he would splash, because if it was *this* time of year (February), I don't think he'd splash in the water. I think he'd crack!"

The teacher then reads on. The next portion of the text concerns the diet of the bear cubs. The teacher has earlier made the prediction that the bear cubs are no longer nursing, sharing her reasoning that they now go in search of stream water. In this portion of the text, it becomes clear that the cubs are indeed still nursing. The teacher corrects herself: "They are still nursing. They are still taking their mother's milk. Mine wasn't a very good prediction then, was it? I thought that when they said they were drinking water that they had finished drinking their mother's milk."

However, Kinata reassures the teacher: "Well, that was a good prediction. It just didn't come true."

The initial studies of Reciprocal Teaching were conducted over 20 consecutive days with naturally occurring groups of 4 to 17 junior high students who were accurate decoders but poor comprehenders. Unlike Informed Strategies for Learning and Response Elaboration, Reciprocal Teaching is designed for small group instruction with a maximum of eight children per group as an optimum size. Response to the intervention was assessed with measures of students' ability to answer recall and inferential questions, comprehension assessment given in social studies and science classes, and measures of strategy use. Based on these measures, 70 percent of the experimental students attained criterion performance as compared with 25 percent of the control students who were instructed by the same teacher but received isolated skill instruction.

In the most recent extension of this research program, Reciprocal Teaching was investigated with 1st and 2nd graders determined to be at risk for academic difficulty. Instruction was conducted by the classroom teacher, working with groups of six children. With these young children, Reciprocal Teaching was conducted as a listening activity. The dialogue presented above is representative of these lessons. The number of days of instruction was increased from 15 to 30, and the effectiveness was evaluated with a battery of comprehension questions.

Seventy-five percent of the 1st grade students achieved criterion performance. An additional finding was that 1st grade students were observed to spontaneously engage their teachers in similar discussion during small-group reading time. Finally, a follow-up conducted when the students entered 2nd grade indicated that they demonstrated excellent recall of the dialogue procedure.

In summary, studies comparing various approaches to teaching strategies for self-regulated reading, while not plentiful, have been fruitful. The results suggest that when teachers and students attend to the processes of reading, students can be taught effective means of learning from text. While the approaches to strategy instruction differ in certain important dimensions (e.g., the explicitness of instruction), there are also shared features. For example, each approach advocates the instruction of strategies in the context of reading extended text. Each approach represents a commitment of time devoted to strategy instruction and engagement of the teacher in providing guided practice and feeoback as the students acquire and independently apply the strategies. Finally, each approach attends to issues of generalizability: Students are provided information regarding the utility of the targeted strategies, are encouraged to engage in self evaluation of the strategies, and are provided practice using the strategies with a variety of materials.

Summary

During the past decade, there has been considerable interest in the role that strategic activity plays in students' self-regulation during comprehension activity. The current portrait of the successful reader depicts someone with a repertoire of cognitive strategies that can be used flexibly to monitor and control reading activity. The selection and orchestration of these self-regulatory activities are a reflection of the learner's self-knowledge and knowledge of the demands of the reading activity. In addition, the successful reader is motivated to use this knowledge. This characterization suggests an instructional agenda that includes (1) teaching students a repertoire of strategic approaches for reading text, (2) teaching students how to monitor their comprehension activity for purposes of flexibly using strategy knowledge, and (3) teaching students the relationship between strategic activity and learning outcomes so they are motivated to engage in self-regulated learning.

A model of instruction for self-regulated learning emerging from the research literature supports strategy instruction as an integrated part of the curriculum, including assessment of current strategy use, explanation regarding the nature and use of the strategies, modeling and guided practice in the use of the strategies, and opportunities to use these strategies across the contexts in which they are useful. The goal of such instruction is to demystify the classroom and increase the opportunities for children to be intrigued and challenged, rather than baffled, by classroom experiences.

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3

Improving Practice Through Understanding Reading

Isabel L. Beck

The reading process—how people turn marks on a page into meaningful ideas—has been a phenomenon of curiosity and study for over 100 years. In the first decade of this century, psychologist Edmund Burke Huey published a landmark book on reading. In it he pointed out that a complete understanding of reading would require comprehending "very many of the most intricate workings of the human mind" (1908/1968).

Some 80 years later, though we do not completely understand how people turn the marks on a page into meaningful ideas, there has certainly been progress. Over the last 15 years, advances in

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cognitive psychology have allowed the study of the mental processes involved in reading, that is, what the reader does while reading. Earlier, researchers had emphasized the products of reading, that is, what the reader remembers. With the current cognitive orientation, progress has been made in understanding how the reader's execution and coordination of the processes affects the products of reading.

A thoughtful understanding of the reading process may be one of the most important contributions to enhancing instructional practice. A thoughtful understanding does not imply the need for formal study of theories or detailed knowledge of numerous studies; rather, an important start to understanding the reading process is an appreciation of the fact that reading is a complex skill. Developing that appreciation is hindered by the fact that reading appears to be such a mundane endeavor. In this regard, Just and Carpenter (1987) make some excellent points:

> An expert can make a complex skill look easy. But the apparent effortlessness of a chess master or concert pianist does not deceive us. What we sometimes fail to appreciate is that skilled reading is an intellectual feat no less complex than chess playing. Readers of this book are, in many ways, as expert at reading as chess masters are expert at chess. But because of the deceptively effortless look and feel of reading, and the fact that there are relatively many "reading masters" in our society, reading skill is not given as much credit for complexity as other forms of expertise. Its complexity is also one reason why not everyone learns to read, and certainly not everyone becomes an expert reader.

My conception of the reading process is based on work done by cognitive psychologists, particularly the models presented by Just and Carpenter (1987) and Perfetti (1985). In this cognitive view, reading comprehension is not a single process; rather, it is complex and made up of many interrelated component processes.

The mental operations involved include recognizing words and associating them with concepts stored in memory; developing meaningful ideas from groups of words (phrases, clauses, sentences); drawing inferences; relating what is already known to what is being read; and more. For a reader to comprehend a text, all these mental operations must take place, many of them concurrently. Yet work in cognitive psychology has uncovered an apparent conflict in the fact that human information-processing capacity is limited. People simply cannot pay active attention to many things at once. Hence, there is a conflict between the fact that reading requires the reader to coordinate a number of mental operations and the fact that human information-processing is limited. Theorists have resolved this conflict by underscoring the point that when a skill such as reading comprises a number of processes, some must be developed so they can be carried out automatically, or efficiently. An efficient skill can be accomplished without much, if any, direct attention.

Efficiency of process is an important part of the current view of reading as an interactive process. This view contrasts with earlier hypotheses that reading proceeded in sequential steps in either a bottom-up or a top-down process. For example, suppose reading were composed simply of print and ideas. According to the bottom-up view, we would attack the print to get to the ideas; that is, we would proceed from identifying words to putting them together into meaningful units—clauses and sentences—and eventually gain meaning from the text. In the opposite view, reading proceeds top-down, with our ideas about the meaning of a text leading to hypotheses about the information on the page and to confirmation or rejection of the hypotheses through a sampling of the print.

The interactive view assumes that information from print and from the conceptual arena acts simultaneously to influence each other (Just and Carpenter 1987, Perfetti 1985, Rumelhart 1977a, Stanovich 1980). As we perceive visual information from text, we call on a number of sources of knowledge. These include awareness of letter-sound correspondences and spelling patterns, knowledge of word meaning, knowledge of syntactic possibilities and language patterns, and memory of the preceding context. The sources interact to help us compile information about the textual input, identify it, and integrate it with what has come before. Thus, meaning of the textual message is constructed.

For example, in reading the sentence, "Mr. Jones searched the shelves for the *book*," identification of the word *book* might call three sources into play: background knowledge that books are often kept on shelves; memory for previous context (i.e., the definite article *the* points to the likelihood that a specific book was mentioned earlier); and knowledge of spelling-sound correspondence (i.e., *b*, *oo*, *k* forms the word book). Identification of *book* would not be as efficient if context, previous knowledge, or information about spelling-sound mapping failed to supply information.

A point implied above, and one that is emphasized in the current view of reading, is that comprehension is constructive because the meaning of a text is built by the reader, not extracted from the pages.

At issue here is that no text is complete in itself. It can't be because the nature of language precludes it. Readers must use prior knowledge to fill in gaps, make inferences, and determine what text information relates to what. The constructive nature of comprehension can be seen in the two sentences below:

> At the end of the intense conversation, Humphrey asked his brother to lend him 25 dollars. Reluctantly, he reached for his checkbook, wondering whether his promise would be good this time.

When competent adult readers are asked about the promise and why the brother was reluctant to lend the money, most of them answer that the promise was to pay the money back and the reluctance was because Humphrey did not pay back previous loans or was always late in doing so. None of that information is presented in the sentences, but most adults suggest this interpretation. They do so because they bring to the text their knowledge of the conventions of lending (it means being paid back) and their knowledge of human reactions (reluctance is caused by something, and not being paid back is a plausible cause in this context). Thus, the reader uses information from the text and information already available in memory to construct meaning.

The rest of this chapter details three areas where we have advanced our understanding of the reading process. The first section elaborates on how recent work has demonstrated the need for word recognition efficiency. This section also presents instructional suggestions for its development. The second section, Text Structure, deals with how the organization of a text influences what is understood and remembered, as well as how instructional repertoires might be enhanced by understanding features related to coherently organized text. The third section, Background Knowledge, discusses the profound influence that a reader's knowledge of the topic of a text has on comprehension, and suggests that instructional implementation of this notion can be improved through increased understanding of the role background knowledge plays in comprehension.

Word Recognition Efficiency

As noted earlier, when a skill such as reading comprises a number of processes, some of them must be developed so they can be carried out without direct attention. In reading, word recognition must be developed to the point where it is carried out efficiently. If it is not, there may not be enough mental processing capacity to attend to some of the higher-level processes involved in comprehension, such as constructing meaningful phrases and sentences from groups of words, drawing inferences, and relating what is already known to what is being read (LaBerge and Samuels 1974).

A number of researchers have reported strong correlations between the speed and accuracy of word recognition and reading comprehension. (See Perfetti 1985 for a review of these studies.) Perfetti explains these findings by pointing out that some of the processes involved in reading must occur at the same time. Therefore, if one process is slow and inaccurate, the information that it provides to the rest of the reading system will not be completely available when needed by other processes, and overall reading performance will suffer.

This negative impact is easily recognized in the psychomotor domain. For example, compare a competent and novice basketball player as each dribbles during a game. The competent individual dribbles efficiently, giving no conscious attention to the activity. He can direct attention to higher-level components of the game, such as avoiding a steal, getting into position to pass, or maneuvering to a place where the ball can be dunked.

Now think of a novice who needs to pay a certain amount of conscious attention to dribbling to do it well. If the novice devotes too much attention to dribbling, the higher-level components such as passing and shooting cannot be performed successfully. If the novice diverts attention to these components, the dribbling ability could break down, and he might lose the ball.

In reading, word recognition is considered a lower-level process, like dribbling in basketball. Given the current view that some reading processes must be engaged in parallel, weak word recognition can be one cause of poor comprehension because the reader does not get word information to semantic processes accurately and quickly enough. This robs attention from comprehension processes.

Efficient word recognition develops through practice. A problem is that there are huge differences in the amount of practice different individuals need to become efficient at word recognition. Indeed, as early as several months into 1st grade, some children are far less fluent at word recognition than others, as measured by precise laboratory methods (Lesgold, Resnick, and Hammond 1985). And for some students, time alone does not take care of the problem. Older, less-skilled readers frequently manifest inefficient word recognition abilities (Frederiksen, Warren, and Rosebery 1985a, 1985b).

The notion that efficient word recognition is required for skilled reading has long been acknowledged. But until the last decade or so, few attempts were made to provide training in this skill to those who did not develop it spontaneously. Now that researchers can explain in detail why efficient word recognition is required, several intervention studies have been undertaken from which instructional implications can be gleaned (although not all attempts to train efficient word recognition have been successful).

Fleisher, Jenkins, and Pany (1979) trained poor readers to recognize a small set of words until their speed equaled that of good readers. But the subjects' comprehension of passages made up of the words they practiced was not improved. The researchers suggested that such short-term training with isolated words is not adequate to affect comprehension; practice may need to target words in context.

Another possible cause of these results, however, is that students with inefficient word recognition skills are overly dependent on "sight" knowledge of words. Sight training on a small set of words does not build readers' knowledge of and efficiency with the print-to-speech mapping system. In contrast, skilled readers recognize words efficiently because their knowledge of spelling patterns allows the simultaneous activation of overlapping sub-word units (e.g., letter clusters, syllables, phonograms). Hence, less-skilled students need training that requires them to attend to sub-word letter strings in the course of word recognition rather than to sight recognition of a small set of words.

This possibility was tested by Beck and Roth (1984a, 1984b) with two computer programs designed to provide intermediate-grade, less-skilled students with enormous amounts of practice in identifying and manipulating sub-word letter patterns to form and recognize words in environments requiring subtle discrimination of letter patterns. This training led to substantial increases in the accuracy and efficiency of word recognition. Moreover, the improvements were not specific to words that appeared in training. The increased fluency led to improvement in students' ability to comprehend phrases and short sentences (Roth and Beck 1987).[1]

[1]It should be noted that Roth and Beck (1987) found no improvement in comprehension at the passage level. The investigators suggest that word recognition improvements may eventually manifest at the passage level when other inadequate components of comprehension are addressed.

The training technique that is most easily implemented in classrooms is "repeated readings." The idea of reading a selection a number of times is not new. Indeed, Huey (1908/1968) pointed out that in a number of countries, including the United States, many children learned to read by practicing a selection until they could read it with facility. The method lost favor in the classroom, but in the last dozen years several researchers have investigated the technique.

The best known repeated reading research is by Dahl and Samuels (1979) and Samuels (1979). In these studies, children read a short, meaningful passage out loud to an adult several times until a criterion level of fluency was reached. In between reading the passage to the adult, the children practiced reading the passage on their own. When a satisfactory level of fluency was reached, the procedure was repeated on a new passage. In Samuels' study, students not only improved in fluency on each passage, they also showed a transfer-of-training effect in that the first reading of each new passage was faster than the previous initial reading had been, and the number of readings to reach criterion decreased. The most important finding was that there was improvement in comprehension.

Chomsky (1978) used a version of the repeated reading technique with 3rd graders experiencing reading failure. The children read along in books as they listened to audiotapes of the text. Chomsky reported enhanced progress in reading class and greatly improved attitudes toward reading as results of the technique.

Support for repeated readings, both with and without audiotapes, was recently reported by Dowhower (1987). Seventeen 2nd grade students whose reading rate was below average showed improvement in rate, accuracy, comprehension, and meaningful phrasing as a result of repeated readings.

There appears to be growing evidence that various versions of rereading meaningful selections produce positive results. Samuels' study was labor intensive in that children read aloud to an adult, but many variations can be used: reading to peers, parents, and student tutors, as well as following along with an audiotape or as a teacher reads to a group. In a "reader's theater," students can be assigned to read aloud the narrator and character parts of a story, or older students can develop audiotapes for younger children to use for rereading.

The instructional message from this research is that "practice makes perfect." However, all practice activities are not equally successful. Moreover, no universally ideal practice has been identified, nor is that likely.

Text Structure

It is obvious that some texts are harder to understand than others, and educators have long been concerned with providing students with comprehensible texts. This concern is most often manifested in readability formulas that predict the difficulty of a text by considering sentence length and vocabulary difficulty. However, these two variables do not influence comprehension directly. When content is kept constant, simplified vocabulary and shortened sentences do not necessarily result in text that is easier to comprehend. Over the last decade, scholars have presented a variety of elaborate linguistic analyses that point to the inadequacies of the formulas, but the use of readability formulas persists for several reasons.

Readability formulas do serve a broad sorting function (they identify text that is obviously inappropriate for a given grade level), and they are objective and easy to apply. Probably most important, there is nothing as objective and easy to apply with which to replace them. But are readability formulas a serious disservice to instructional practice?

My concern is that readability formulas discourage teachers from thinking about the different demands texts make on their students' skills and knowledge. Consider a 6th grade basal reader with about 50 different selections. The majority of the readings are narratives, but biographies, plays, expositions, and poems are included. While each of the selections bears an acceptable 6th grade reading index as calculated by a reading formula, the selections are not alike in terms of features that will affect comprehension. Just because the text has been judged acceptable for 6th grade does not mean all students at that level will be able to use it successfully. And if students have difficulty, teachers may wrongly assume that the instructional remedy is to simply move the student back to an easier level. The proper response would be to consider the text features that might affect comprehension.

In the present period of reading research, investigators have been able to describe text features that influence comprehension directly by taking into account how texts are organized and how readers represent incoming information in memory. And a key to this work is relationships—relationships between and among words, between and among sentences, and between and among larger segments of discourse.

The most well-known attempts to understand how the relationships between larger segments of text affect comprehension have focused on narratives and have produced analyses of stories known as "story grammars" (Rumelhart 1977b, Stein and Glenn 1979, Thorndyke 1977). A story grammar consists of categories that describe a well-formed story: *setting*, in which the protagonist is introduced; *initiating event*, in which something causes a response in the protagonist; an *internal response*, which often involves the protagonist's decision to pursue a goal; an overt *attempt* to achieve the goal; a *consequence*, in which the attainment or nonattainment of the goal is marked; and a *reaction*, which includes the protagonist's response to the consequence.

Research has shown that in reading a story, readers expect information that will fill each of the story grammar categories. When stories lack one or more categories, or when the categories are presented out of order, comprehension is depressed in terms of less recall of story information (Stein and Glenn 1978) and more distortions and confusions within the recall, particularly for younger students (Mandler 1978).

It appears that well-formed stories facilitate comprehension, and stories that deviate from the expected structure disrupt comprehension. But deviation from the expected may also be caused by complex stories (for example, those that contain flashbacks and embedded episodes). It is reasonable to want to exclude poor stories from instruction, but it may not always be possible to do so. Nor do we want to exclude from instruction all stories that deviate from the expected because of their complexity. In either case, the implication of the research is that teachers should be aware that a story with a complex structure needs more instruction than a simple, invariably structured story. Thus, even in the case of narrative, the most common genre used in reading instruction, in any given grade level there will be easier and harder selections. All stories, even those with the same readability level, will require different instructional attention.

Familiarity with story grammar is useful for those who interact with students and texts. A generalized understanding of the structure of narratives and the ability to recognize when the plot of a story contains gaps or is particularly complex may help teachers identify potential difficulties.

Other research on text organization has looked at smaller units of text called propositions. Propositions are simple clauses, and their organization in text is assumed to characterize the structure of a text that forms as a reader reads. An important focus of research at the propositional level concerns the influence on comprehensions of the actual statements of the relations among the propositions of text.

That is, to what extent does the way those ideas and events are stated clarify their nature and their relationships? These issues are often referred to as coherence.

A large body of research holds that the coherence of texts affects their comprehensibility. Characteristics of text that bear on the coherent statements of events and relations have been described in various ways. Trabasso, Secco, and van den Broek (1984) discuss qualities of texts that lack coherence. These include poorly ordered statements that inhibit comprehension of cause-effect sequences, the inclusion of irrelevant details, or new, unrelated sequences within one that is being presented. Anderson and Armbruster (1984) characterize such "inconsiderate texts" as those that lack "signaling" to emphasize key ideas, and include relationships that are not explicit, event sequences that are out of logical order, and references that are unclear.

Beck, McKeown, Omanson, and Pople (1984) focused on many of those characteristics in revising several basal selections to make them more comprehensible. They found three categories of problems. The first category concerned problems with the surface form of the text, such as difficult referents or omitted grammatical categories. The second area was the nature of the content, such as implied events, ambiguous words, or poorly drawn relationships between events. The third problem area was the knowledge assumed by the text, such as the use of an event sequence that demanded information likely to be unfamiliar to targeted students.

It is not important to learn the labels of the various categories, for different researchers label a particular text feature differently, and often certain text problems seem to fall into several categories. The categories need only be used as far as they help organize an understanding of problematic text features. Although these features may not present obstacles for the mature reader, the effect for young or less-skilled readers may be different. The effect is particularly serious when a selection has several of these problems.

First, consider an example of a difficult reference:

> " 'This knife is worn out,' Bill cried. He took the old implement and threw it into the rubbish can."

This excerpt takes a somewhat sophisticated understanding of the use of references to realize that "old implement" refers to the knife. Problems can arise with the use of pronouns as well as with alternate labels, and can be compounded in a text by distance from the referent or intervening nouns that may cause a reader to relate a reference to an incorrect referent.

Next consider an example of a poorly drawn relationship between two text ideas:

"Henry hoped his brother would take him camping for his birthday. His birthday would be no fun."

The problem here is that the connection between these two ideas is missing: Henry's birthday will be no fun *if* his brother *does not* take him camping. Note that coherence could be improved simply by adding "if they didn't go camping" to the second sentence.

Now consider an example of an ambiguous text segment:

"When everyone saw Fred in his new suit, they nodded and smiled at each other."

It is not apparent from the sentence whether everyone is giving approval to Fred's suit or laughing at his taste in clothes. If the reader draws the wrong interpretation, or is left unsure of which interpretation to draw, comprehension is disrupted.

One final example is a text sequence that contains an irrelevant idea in its midst:

"Ruth ran into Terry in the store. She was shopping for some new shoes. It was good to see Terry again. She hadn't seen her in a long time."

The sentence about shopping for shoes may lead the reader to believe that is the focus of the sequence. Processing of the subsequent sentences about Terry may be disrupted as the reader tries to sort out the relevance of shoe shopping to Ruth and Terry's reunion.

When teachers are aware of the kinds of text features that may be problematic, they can help students deal with them. One way is to highlight aspects of the text that have problems. Discussion before reading and questions after can guide students toward thinking ways that may promote comprehension despite the limitations of the text. Suppose that the example about Fred's new suit was preceded by a segment about Fred encountering a slick salesman who convinced him to buy an outlandish outfit. The teacher could prepare students to realize that the upcoming text represents people snickering about Fred's appearance. Questions might be posed such as, "What did Fred's new suit look like? How do you suppose Fred thought he looked? What might other people say or think about Fred's new suit?"

A particularly useful technique involves modeling the mental process involved in understanding an ambiguous text passage. Using the excerpt about Henry's birthday wish, a teacher might read aloud, "Henry hoped his brother would take him camping for his birthday. His birthday would be no fun." Then the teacher could demonstrate that the excerpt caused some comprehension difficulty: "No fun? Why wouldn't his birthday be fun?" And then he could go on to work out the problem, beginning with rereading the first sentence. "Henry hoped . . . oh, he wanted to go camping, so if his brother *didn't* take him camping, then his birthday wouldn't be fun." In this way, a teacher illustrates that texts are often incomplete and demonstrates the kind of reader input that might be needed to solve problems. Exposure to models of a skilled reader's processing can help students anticipate problematic text situations and develop a basis for dealing with them (see Palincsar and Brown, chapter 2).

A word of caution about using the label "problematic" for text features: Problematic text features can be caused by poor writing or inadequate explanations. However, not all problematic features are caused by low-quality writing. Indeed, the writing may be of high linguistic quality but difficult to process. As such, many students may need some help to learn to handle such features. Consider the way Ms. McFarland helped her 9th grade English class appreciate how a magnificent writer like Charles Dickens used language to produce the psychological effect on readers that he desired.

Ms. McFarland's introduction to *Great Expectations* included reading aloud the first chapter, which contained the following description of the convict:

> A fearful man, all in coarse gray, with a great iron on his leg. A man with no hat, and with broken shoes, and with an old rag tied around his head. A man who had been soaked in water and smothered in mud, and lamed by stones, and cut by flints, and stung by nettles, and torn by briars; who limped and shivered, and glared and growled; and whose teeth chattered as he seized me by the chin.

After Ms. McFarland read that part, she looked up and slowly said:

> "What a frightening man. Hmm, every time I read Dickens I find myself in awe of the effect his use of language has on me. Those sentence fragments, how effective. . . . A man soaked in water, and smothered in mud, and lamed by stones,

and cut by flints, and stung by nettles, and torn by briars, who limped and shivered, and glared and growled; and. . . ."

By thinking aloud, Ms. McFarland modeled some of the mental processes she used during reading. Her reflections about the effect Dickens achieved with sentence fragments resulted in several members of the class noticing their use in other places, as well as the use of other atypical constructions.

The Dickens example illustrates that problematic text is not necessarily of poor quality. But no matter what is causing the situation, the instructional issue is that all texts at the same grade level are not equal and teachers need to become aware of the situations that can impede comprehension and help students cope with them. Teachers need to be actively involved in the text itself when they prepare students to read and to discuss the text after students have read it. Active involvement does not imply the need to engage in deep linguistic analysis; rather, awareness of the kinds of text features that are potentially difficult can alert teachers to potential problems. In this regard, Pearson (1974-75) has suggested that those who write selections be guided by the question, "What is the best way to communicate a given idea?" When teachers identify potential problems, they need to consider a similar question, "What is the best way to help students handle this kind of text feature?"

Davidson and Kantor (1982) have suggested that the best substitute for readability formulas is informed judgment. Informed judgment requires knowledge of language, literary style, and how best to communicate the specific content and its relationships, and especially knowledge of what causes people problems in processing text. One way to develop that knowledge is to read text and consciously monitor your comprehension processes to recognize when you're doing extra work. Extra work could include having to reprocess portions of text to understand a passage, or needing to call on sophisticated levels of linguistic or world knowledge. Teachers who find themselves doing extra work when reading a passage can be reasonably sure that their students will also encounter difficulty and may not be able to resolve the problem without some help.

Background Knowledge

The current understanding of the constructive nature of reading underscores the contribution of the reader's background to comprehension. It is, of course, obvious that there is a relationship between what we know about a topic and what we comprehend when reading about it. Current research has gone beyond the obvious to explain why background knowledge effects comprehension and to suggest strong implications for instruction. Although the importance of background knowledge was acknowledged in the past at a general level, it was not at all clear that practitioners considered inadequate background knowledge when attempting to understand why certain students were having comprehension difficulty.

Lack of background knowledge may not typically be targeted as a reading problem because its effects can be subtle, although most competent adult readers have experienced or at least observed it. Consider the difficulty a manager of a retail business might have with a *Time* magazine article on genetic engineering. However, the negative impact on comprehension of insufficient background knowledge is not confined to the more scientific and technical domains, nor does it always involve a complete absence of background knowledge. Consider the following text adapted from a 5th grade reading book in light of a reader who knows what baseball is and has a general sense of the rules of the game but whose understanding is not that of a true baseball aficionado.

> "Two out, man on third," Barney chattered as Rex Noyes moved in, a mean look on his face. Rex tapped the plate with the top of his bat and squared off.
>
> Two pitches later, Rex was behind 0 and 2. Dusty wasted the next pitch, but Rex wouldn't bite. He protected the plate until he had worked Dusty to a full count.
>
> On the next pitch, Rex hit a screamer to Herbie at short. It was too hot to handle and Herbie juggled it for a moment. His peg to Barney was wide and low and Barney was pulled off the bag. Fortunately, he dug it out and prevented Rex from advancing.

Without adequate knowledge of baseball jargon, it is unlikely that the reader would comprehend this text. Indeed, informal tryout of the text with educated adults as well as several intermediate-grade students with enough baseball knowledge to follow most of the main events of a baseball game showed very little understanding of the text. It appears that a reader, even an adult reader, who has only a basic knowledge of baseball's rules, typical actions, and overall goals will not understand much of this 5th grade text. A reader can have some familiarity with a topic but not possess enough background knowledge to comprehend a text on that topic.

Recent research has looked at the effectiveness of some instructional strategies designed to provide background knowledge to students before they read. Two types of strategies have been developed in this research—those that help students use knowledge they already possess and those that impart new concepts.

Studies that address helping students use knowledge they already possess assume that comprehension may suffer when students have knowledge relevant to the content of the text but have difficulty linking what they know with concepts in the text. One such set of studies (Langer 1981, Langer and Nicholich 1981) addressed the effectiveness of an activity called Pre-Reading Plan (PReP), which helped students access relevant knowledge before reading. PReP has three phases: (1) the teacher asks students to free associate about a concept that will be important in the upcoming text, (2) students explore why they came up with their associations, and (3) they discuss any new ideas about the topics as a result of the activity. In addition to helping students activate knowledge they may have, the PReP activity also measures students' background knowledge and enables a teacher to determine if student knowledge is adequate for the selection. Langer and Nicholich (1981) showed that judgments about students' levels of knowledge based on PReP were good predictors of the student comprehension. With high-, average, and low-skilled 6th grade readers, they found PReP influenced comprehension for the average group only. The authors reasoned that high-skilled readers could do for themselves what the PReP activity did for the average readers, whereas low-skilled readers needed direct concept instruction as opposed to refined concept awareness. These results suggest that the PReP activity may be an effective tool for boosting comprehension for some readers and for alerting the teacher that some students need further preparation before reading.

Graves and his colleagues have conducted research on the effectiveness of instruction aimed at increasing background knowledge by imparting new concepts to students before reading (Graves and Cooke 1980, Graves, Cooke, and LaBerge 1983, Graves and Palmer 1981). Graves created short story previews designed to present relevant background knowledge and to introduce specific key story elements (characters, plot, point of view, and setting). The previews began with questions to elicit discussion of concepts related to the text. Then the teacher read a 400- to 600-word text. Four separate experiments involving upper elementary, junior high, and senior high students yielded significant results for both high- and low-skilled readers. Although these previews involved more than increasing general knowledge, their results suggest that increasing a student's knowledge may be an important step toward improved comprehension.

Beck, Omanson, and McKeown (1982) tested 3rd graders' comprehension of traditional basal reading selections when they were presented with the introductory material prescribed in the teacher's manual and compared it with the performance of students who received revised versions of the introductory material. The original version often dealt with ideas that were tangential to the plot; the revised version focused on concepts central to the story's meaning. Students who received the revised lessons recalled more of the story and correctly answered more questions, including those about implicit information, than did the control group. Here, as in Graves' studies, background knowledge was not the only issue. However, the results again support the idea that greater background knowledge of ideas relevant to the selection enhances text comprehension.

The instructional implication of this work is that teachers need to prepare students for reading by establishing and activating relevant background knowledge. But the idea of supporting students by providing background about the content in an upcoming text is far from new. In fact, the notion of enhancing comprehension by building background knowledge has been institutionalized in basal reading programs, the major vehicle for reading instruction in the elementary grades. The typical prescribed format for lessons begins with a preparation phase where a teacher-led discussion is intended to provide background knowledge, such as the story setting and new concepts to be encountered in the selection, and to elicit relevant personal experiences from students. The problem, however, is that the quality of instructional suggestions provided in teachers' manuals is variable (Beck, McKeown, McCaslin, and Burke 1979). One of the major problems with these lessons is that the concepts chosen for discussion before reading are, as noted earlier, sometimes tangential to the central ideas of the selection and thus not always useful for preventing potential background knowledge problems.

A major instructional issue, then, is how teachers decide what content needs to be presented. There is, of course, no algorithmic procedure for selecting content for pre-reading attention. But when teachers have a deep understanding of how fundamental background knowledge is to reading comprehension, they tend to make good judgments (Beck 1986). Teachers in master's-level university classes were asked to develop a pre-reading lesson for a typical basal reader selection. Then they were presented with theory and data associated with the role of background knowledge. Finally, they were asked to redesign the pre-reading lesson. The second attempt virtually always evidenced a better selection of the content to be presented than the first attempt, and better activities than suggested in the teacher's manual. Of particular importance is that all of the participants were experienced teachers who were acquainted with the relationship between background knowledge and comprehension and who had specifically acknowledged its importance before the first assignment. However, after they had engaged in a sequence of experiences designed to underscore its importance, the quality of their instructional implementation of this notion improved markedly.

A Final Comment

Research on the constructive nature of reading and on the processes involved in this complex skill has yielded a deeper and richer description of reading than was previously available. This discussion of word recognition efficiency, text structure, and background knowledge was intended to show that understanding these topics, and their interrelated roles in the complex reading process, may yield beneficial instructional insights. Each of these aspects of the reading process can negatively affect students' comprehension. Thus, an appropriate instructional intervention cannot simply be a matter of placing a 3rd grade basal reader in the hands of a 4th grader who is having comprehension difficulty. Each teacher must assess the cause of a student's difficulty by integrating knowledge of the individual students with an understanding of the reading process. A student may be having difficulty because her word recognition skills lack efficiency, or because she has never before encountered a flashback in a story, or because she has lived her life in a small town and the story is about a young boy's trip on a subway.

It is impossible to anticipate every classroom situation in the abstract and to arm teachers with specifically appropriate instructional techniques. But appreciation of how the processes of reading work and understanding why certain conditions produce certain outcomes can enhance teachers' instructional repertoires.

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4

Teaching Mathematics Concepts

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Spurred on by recent disappointing reports about the mathematics achievement of American children (Carpenter, Matthews, Lindquist, and Silver 1984; McKnight, Crosswhite, Dossey, Kifer, Swafford, Travers, and Cooney 1987), mathematics educators have shifted from a back-to-basics drill and practice orientation to an emphasis on developing children's problem-solving and critical-thinking skills (National Council of Teachers of Mathematics 1980. 1987, Romberg 1984). The new orientation usually stresses teaching children how to identify key aspects of problem situations and to use particular strategies to arrive at solutions (Pólya 1973, Sowder, Threadgill-Sowder, Moyer, and Moyer 1986, Whimbey and Lochhead 1986). This approach encourages more than simple rote learning, but it still treats mathematics as an objective body of knowledge and techniques that can be transferred in a more or less unaltered form to the minds of receptive learners.

Research in cognitive developmental psychology indicates, however, that to be effective, education must also take into account the child's contribution to the learning process (Piaget 1973). Educators must consider how children interpret the accepted body of knowledge, both content and technique. In particular, recent research has provided insight into the nature of children's creative mathematical activities and how they affect the learning of mathematics (Carpenter, Moser, and Romberg 1982, Ginsburg 1989). This chapter presents some key findings from this body of research and describes several ways they can lead to more effective teaching practices.

The Nature of Children's Mathematical Thinking

Cognitive developmental research shows that children possess a mental framework for interpreting experience in and out of school. This framework evolves as children grow older, but it colors and shapes the way children at all ages interpret what they are taught. Knowledge of mathematics is not simply acquired from some external source but is actively constructed by the child (Carpenter 1985, Cobb 1985, Erlwanger 1973). In Piaget's phrase, children "invent" mathematical knowledge through their own observations and interactions with the environment.

Informal Knowledge

This active invention begins before the child enters kindergarten and takes the form of informal mathematical knowledge. This is knowledge that need not be acquired in the context of formal schooling, but seems to be developed primarily through spontaneous interaction with the environment and through imitation of adults. Research has shown that one of the earliest concepts to develop in this domain is the notion of "more," and that this knowledge is followed closely by an ability to appreciate the effects of addition and subtraction operations (Gelman and Gallistel 1986). Research shows further that these concepts gradually become elaborated so that by 4 or 5 years of age children know that the spoken word "seven," for example, indicates a larger number than the word "three" (Ginsburg and Russell 1981), and that two or more groups of objects can be combined and counted to determine how many objects there are "all together." As time goes on, children refine such concepts (Resnick 1983) and develop increasingly efficient strategies for combining large groups of objects. By age 5 or 6, for example, children create for themselves the strategy of adding by "counting on": they combine two groups of objects by beginning with the cardinal number of one set and counting up only the objects in the second set (Groen and Resnick 1977). For example, asked to add one set containing eight pieces and one containing six, the child will count. "8, (pause), 9, 10, 11, 12, 13, 14. Fourteen all together." Children will also figure out that counting on is even easier if one begins with the value of the larger set, regardless of which set is presented first (Fuson 1982). So, for example, if children are shown a group of four and then a group of seven and asked how many there are all together, they are likely to count, "7, (pause), 8, 9, 10, 11. Eleven all together." It is clear that children can develop this kind of informal knowledge simply from repeated experience with counting objects and using the quantitative vocabulary of everyday life. This informal knowledge then forms the foundation for learning in school where children encounter formal mathematical concepts and procedures.

Formal Knowledge

The formal mathematics taught in school is a highly organized, codified, and written system, developed over the centuries, and typically transmitted through a process of systematic instruction. In the first few years of school, children are exposed to ideas and tools that could be more powerful than their informal concepts and procedures. They are taught symbolic means to represent mathematical ideas and procedures, concepts such as place value, and the basic techniques of calculation. This is what they are taught. But what do they learn? Because children assimilate school-taught mathematics into their existing mental framework, they often develop some rather unique or nonstandard procedures for doing arithmetic. For example, some students solve computational problems by "invented procedures," methods they create at least partially by themselves. These inventions blend the informal and formal; they typically draw on what the child already knows to modify what is taught in school. For example, when first learning written double-digit arithmetic, children may work their computations from left to right. This procedure parallels one of the ways children do mental calculation, by adding the tens numbers and then counting the ones, as in "well, 20 + 23 is 20 + 20 makes 40 and then 41, 42, 43."

These procedures can be remarkably effective and can be used with comfort and ease. Sometimes, however, children's inventions are less effective and lead to the development of "bugs," or systematic error strategies. These procedures are systematically defective and in certain situations (but not necessarily all) result in regular, predictable errors (Ashlock 1986). For example, a child who subtracts 18 from 32 and gets the answer 26 is usually overgeneralizing the rule that one must always subtract the smaller number from the larger.

That is, to solve the problem:

$$\begin{array}{r} 3\ 2 \\ -\ 1\ 8 \\ \hline ? \end{array}$$

. . . the child subtracts all smaller numbers from all larger numbers:

$$\begin{array}{r} 3 \\ -1 \\ \hline 2 \end{array}$$

and

$$\begin{array}{r} 8 \\ -2 \\ \hline 6 \end{array}$$

. . .and incorrectly gets the answer:

$$\begin{array}{r} 3\ 2 \\ -1\ 8 \\ \hline 2\ 6 \end{array}$$

In this example, the child's systematic error strategy produces an error, but in other situations the rule leads to accurate computation (e.g., 38 − 12 = 26). Although to an adult these thought processes may seem meaningless, they make sense to the child using them. Because the child's errors reflect an interpretation of what is taught, they can be considered as clues to thinking processes rather than indicators of lack of learning.

Research also shows that sometimes children suspend sensible mathematical thinking to memorize a seemingly meaningless and arbitrary collection of algorithms. In these cases, children's informal mathematics often fails to exert a salutary influence on their formal knowledge. The two systems seem to operate independently, each according to its own "logic." For example, some children who determine by counting that 22 chips plus 19 chips are 41 chips can be perfectly comfortable maintaining that when written numbers are involved, 22 + 19 = 311 because 9 + 2 is 11 and 2 + 1 is 3. Children may even believe that both answers are equally correct because they were obtained in different ways.

Another example of the blending of children's reasoning and school-taught procedures comes from observations of children's conceptions of the "borrowing" or regrouping procedure in subtraction. One rather interesting bug that the authors observed was of a child who always regrouped for addition or subtraction when the bottom number in the units column was larger than the top number. Thus, to solve the addition problem 42 + 13, the child crossed out the 4 and "made it 3" and then "made the 2 into a 12." Then she added 12 and 3 by counting and got 15. She put a 5 in the ones column, but disregarded the 1 for the tens column because she believed that she had already done enough with that column in the first step of the regrouping procedure. Then she added the 3 and the 1 that remained in the tens column and obtained the answer 45.

Other children can rattle off number facts quickly—and often correctly—and use them to work out written multiplication problems. Yet when asked to check their answers using an informal procedure—for example, by counting groups of tallies—many of these children are helpless. They cannot determine whether $3 \times 8 = 32$ is right or wrong since they do not see how the world of written numbers relates to anything else. Unfortunately, this rigid approach to school mathematics is all too common. For many children, school mathematics is meaningless.

Children's difficulty should remind us that genuine understanding of mathematics is more than memorizing number facts or using algorithmic procedures to get correct answers. It is more than the acquisition of discrete skills, accurately applied. As Ginsburg and Yamamoto (1986) have noted, genuine understanding must involve the creation of harmonious links among informal and formal procedures and concepts. To understand means to know that a number fact makes sense in terms of counting, or that an algorithm is based on a principle, or that a principle relates to "common sense." To understand means to know that $4 + 2 = 6$ because you can get that result by counting on your fingers, or that column addition works because it is based on the base ten system, or that the base ten system works because it is "just like counting by tens." Learning mathematics, then, is not just acquiring behaviors or getting right answers; it is learning to think.

Beliefs

Research has also shown that children's mathematical thinking is influenced by beliefs about the nature of mathematics and about teachers' expectations. For example, many children believe that the goal of mathematics problem solving is to find the single correct answer as determined by the teacher. For these children, problems are seen only as opportunities to find and apply proper computational rules to some arbitrary set of numbers (Kaplan, Burgess, and Ginsburg in press). While the computations may be performed quickly and successfully, they are often unrelated to the meaning and content of the questions themselves. For example, a child might say that the solution is 4×24, but if challenged will just as quickly say, that then it must be 4 plus 24. Similarly, many children believe that mathematics is getting right answers quickly without thought. Indeed, these children may believe that to think is to cheat (Baroody, Ginsburg, and Waxman 1983). For example, if the child has just computed that 12 + 19 = 31, and is then presented with 19 + 12 = ?, there may be a feeling that it is cheating simply to take the shortcut of using the previous answer (which is correct because of commutativity) and that it is necessary to go through the laborious process of calculation all over again.

General Principles of Teaching

Recent psychological research on the nature and development of children's mathematical understanding could and should have an enormous impact on educational practices. The research strongly suggests that the teaching of mathematics is most successful when instruction is adapted to children's thinking processes and natural solution strategies. Children do not learn mathematics merely through exposure to a curriculum, operating in isolation from what they already know. Instead, they assimilate or interpret the formal system of mathematical knowledge in terms of their own mental framework.

Given these considerations, the goal of instruction should be to help children interpret formal mathematics concepts and procedures in terms of their informal, invented procedures and in terms of their beliefs about what is expected of them. To attain this goal, teachers need not only a clear conception of the mathematics to be learned but also an ability to see this knowledge through their students' eyes. This ability consists (at least) of:

- Knowledge of children's typical interpretations of questions, instructions, procedures, and vocabulary of school mathematics at given age levels.
- Knowledge of individual children's unique interpretations of these same topics.
- Knowledge about how to introduce formal mathematics by building on children's existing abilities, by helping children to generalize informal knowledge to new and abstract situations, and by encouraging the formation of connections between what children already know and the abstract representations of mathematics.

Teaching proceeds most effectively when an adult mentor takes into account the child's framework and encourages and guides the child's inquiry and experimentation. Following are a few examples of how this psychological orientation toward mathematics education can lead to particular forms of instruction. These examples consist of:

- The learning of number facts through a series of exercises in discovering patterns and relationships in the multiplication table.
- The development of mental arithmetic strategies as a precursor to written algorithmic computation.
- The use of instruction with manipulatives to expand children's conceptualizations of arithmetic, in particular the multiplication of mixed numbers.

Number Facts

Learning the number facts (sometimes called number combinations) is generally regarded as essential to elementary mathematics education because number-fact mastery is the basis for more advanced computation skills. Children do indeed need to have fast and accurate knowledge of basic number combinations in addition, subtraction, multiplication, and division. However, a premature emphasis on speed and on the rote learning of facts may not be the best way to help most children achieve this goal (Ginsburg 1989). We first need to understand what it means to know the number facts and then know how to help students view the learning of number facts as an interesting problem instead of an exercise in rote memory and, perhaps, frustration. Seeing that the number facts make sense and can even be interesting is, in the long run, more likely than drill to facilitate automatic production and recall.

Psychological Background

One way children learn multiplication number facts is through memorization. Thus, given "2 × 2," the child responds without thinking, "four." However, children can learn through several other procedures as well, seeking various strategies and shortcuts. For example, the 1 times combinations are easily acquired because children realize that "times one" means only that the answer is the larger number unchanged. The 2 times combinations are also relatively easy because they are the same as doubling, and doubling is something that often is already known from addition facts, particularly for the numbers 1 to 6.

Beyond these combinations, children tend to use counting and known addition facts to derive other multiplication facts. For example, 7 × 2 might first be remembered as 6 × 2 plus 2 more, and 6 × 3 might first be derived as 6 × 2 is "12, and then 13, 14, 15, 16, 17, 18" (i.e., 6 × 2 with 6 more counted on). Children also tend to use skip counting to obtain key combinations. In particular, counting by 5's and 10's is often used to get quickly and effortlessly to multiples of 5 and 10. The 5's and 10's combinations, therefore, tend to be among the first spontaneously remembered. The generation of products for all of the above combinations clearly involves relating knowledge of number patterns to the rows and columns of the multiplication table.

Beyond these particular number patterns, many children are inclined to find shortcuts through the use of "principles." For example, children gradually come to see that 6×3 is the same as 3×6, and that this "order makes no difference" rule holds generally for multiplication. Consequently, children first learn the "easier" combination and then realize that knowing it, they also know the harder. They see that it is necessary to learn only half of the multiplication facts to know them all. This insight is easily recognized by diagonally dividing the multiplication table into two equal sections, one the inverse duplicate of the other.

Children spontaneously use other techniques to facilitate memorization. One of these involves breaking larger numbers into smaller, already known multiplication combinations and then adding up the separate pieces. The next section, on mental arithmetic, gives more detail concerning these kinds of processes. For example, 4×7 is the same as 2×7 twice, so the answer is 14 plus 14, or 28. Strategies like these may not be particularly fast, but they reduce the strain of having to remember too many facts at one time. Moreover, the basis for these kinds of notions can again be seen in the columns and rows of the multiplication table.

We see then that not only do children remember the number facts, they also obtain them, sometimes surprisingly quickly, through calculation and sensible shortcuts. Indeed, most number facts do not have to be memorized by rote; they can easily be calculated or obtained by reason. Moreover, after obtaining the number facts through these various procedures, children should have a sensible way of remembering them. The reasoning should come first, not the memory.

Indeed, an early focus on rote memory may be harmful. One reason is that a stress on quick response and rote memory may produce pressure and anxiety. It may also convey the unintended message that number facts are not supposed to make sense; rather, they are memorized, like phone numbers.

By contrast, the child's natural tendencies to "figure out" the number facts, to derive them from principles (i.e., "order makes no difference"), and to develop labor saving shortcuts for getting them are all sensible, meaningful activities. The child's natural approach is more likely than a stress on quick and meaningless response to lead to an understanding of mathematical relationships. And this understanding in turn can provide the sensible basis for memorizing facts.

Instruction in multiplication number facts, therefore, should exploit children's natural sense-making and efficiency seeking tendencies. One way to do this is through an active exploration of the patterns found in the multiplication table. These patterns both reinforce and facilitate children's own construction of numerical relationships.

Instruction

Our approach toward instruction in multiplication facts draws on the work of Trivett (1980) involving the multiplication table and the work of Rightsel and Thornton (1985) on addition.

Trivett's approach involves an extended period of study of the multiplication table and the patterns of relationships within it. He suggests that the table can be used as a vehicle for understanding mathematical relationships from 2nd grade on into secondary school, and that through the recognition of patterns in the table, students can move on to division, fractions, new base systems, and algebraic structures for rational numbers. He indicates that using the table in this way leads to an extra, almost inevitable consequence—mastery of basic number facts. Trivett recommends that in the early stages of this learning, children work with two charts. One is a products chart that consists of all the combinations written out from 0×0 to 10×10 in the standard format of a multiplication table. The other is the standard table. Using both of these charts helps children to focus attention on the meaning as well as the answers for all the basic multiplication number combinations. Trivett also makes the point that the study of these charts should not be confined to any concentrated period of time, but that their exploration should stretch out over years. Among the activities he suggests are: noticing the variety of number patterns in the rows, columns, and diagonals of the tables (for example, the right end digits of all outside entries are zero); using the multiplication table as a division table; and so on.

Rightsel and Thornton stress reliance on children's natural approaches to mathematics—for example, counting—and a careful ordering of facts so that easier combinations are acquired first and can later be used to derive more difficult-to-remember combinations. Their system also provides children with a variety of ways to construct the same fact. For example, they suggest that children play games in which they are asked to draw a picture of numbers shown to them (such as 4 + 2). After they draw the picture and count up to get the answer, they are then asked to turn the picture upside down (so that the order of numbers is reversed) and describe the result of what happened. Similarly, children are provided with animal-shaped cards on which the two ways of stating the same fact appear on either side (i.e., the front and back of animals). In another card game, children have to match like facts, which reinforces the knowledge, for example, that 4 + 2 is the same as 2 + 4.

A blend of Rightsel and Thornton's approach with Trivett's can provide a powerful method for teaching the basic multiplication facts. This encourages children to search actively for patterns in the table and in an untimed learning situation to construct their own knowledge of the number patterns and numerical relationships in the multiplication table. This method of actively constructing knowledge of the table is systematically based on prior preparation in the meaning of multiplication. Such preparation includes the interpretation of multiplication as a form of repeated addition of equal set sizes represented both concretely and symbolically with dots. The preparation also includes training in the conventional numeration system, in how to read the multiplication table, and in finding and generating numerical patterns in other contexts.

While many approaches encourage students to make sense out of the multiplication table, some instructional techniques involve students in a more active role and encourage them to focus on numerical relationships more than on memorization. Some of these techniques include:

- Ask students to generate some number patterns without any reference to the multiplication table. Have them share these patterns with the class.
- Use the table to locate patterns similar to the ones created without the table. Again, have students share and discuss with the group to increase their observations of relationships among different patterns. For example, the teacher might ask how one pattern is like or unlike another and how a second pattern could be derived from one that is already known.
- Ask children to restrict pattern searches to particular numbers in the table. For example, they might be asked to focus on combinations involving the number 10 and to observe the regularities in multiples of that number. For example, the numbers always end in zero; they are in the same sequence as counting by tens. Doing this helps students build reference points for later reconstructing combi-

nations in the multiplication table (e.g., $4 \times 10 = 40$, because 10, 20, 30, 40).

- Evaluate students on both timed and untimed tests to see which combinations are well memorized, which can be derived with enough time, and which, if any, seem to resist children's learning efforts. This method of assessment is consistent with the method of instruction recommended in that it focuses on meaning more than on memorization.

By extending the number of contexts in which the multiplication table can be examined and dissected by students, instruction and assessment follow the natural constructive and sense-making tendencies of children. This approach leads students to mathematical exploration that many of them would probably not tackle if told only to memorize the table. This approach to learning multiplication facts, therefore, would ultimately provide children with a better grasp of both the ideas and processes of multiplication and, most importantly, make the memorization of the combinations something that is less easily forgotten.

Mental Arithmetic

Mental arithmetic refers to the process of doing calculation without the benefit of written work and particularly without the use or knowledge of conventional algorithmic procedures. Historically, mental calculation has been a valued part of mathematics curriculums and practical life situations involving trade, business, and everyday activities (Carraher, Carraher, and Schliemann 1985, Scribner 1984). In modern technological society, however, mental calculation has come to be an undervalued skill used primarily by shoppers and sports enthusiasts. Certainly it is no longer considered an important part of elementary school mathematics curriculums.

This is unfortunate since mental arithmetic can provide the basis for understanding the reasons behind written calculation and a richer appreciation of key topics in arithmetic like the numeration system, place value, estimation skills, and even algorithmic procedures. Hope (1985) indicates that mental arithmetic can help children develop a sense-making approach to mathematics rather than a fragmented view characterized by slavish application of meaningless techniques. Hope, Reys, and Reys (1987) and Avni (1985), among others, have produced promising models and exercises in the area of mental arithmetic. These can be used in the ordinary classroom to promote skills ranging from basic addition to exponents, negative numbers, and geometry. Next we explain why this approach makes sense from a cognitive developmental perspective, and then we show how mental arithmetic can foster the development of key mathematical ideas.

Psychological Background

Before learning to use symbolic notational systems of numeration and calculation, many children demonstrate a facility for manipulating numbers "in their heads." Some children have been observed to perform mental addition with relatively large numbers before they can even read or write numbers (Court 1923). While most children do not exhibit such precocious development, the ability to perform mental calculation is widespread. Oddly, once children reach school age and receive instruction in written arithmetic, this ability seems to go underground. Either children forget how to use their skills or they bend to the pressure of conventional educational approaches that actively discourage use of all but the standard algorithmic procedures. Before this happens, however, children are capable of many interesting invented mental procedures.

At the earliest level of competence, children can use counting strategies to solve addition and subtraction problems by combining and separating spoken numbers (Baroody and Ginsburg 1986). Some children do this by visualizing arrays and then counting the imagined sets. Other children begin with the cardinal value of one of the numbers and then just "count on" by ones from a second set. Beyond the level of counting, young children are able to solve simple arithmetic problems by using the commutativity rule for addition and multiplication and by applying the complementary relationship of addition and subtraction. Using an intuitive understanding of the associative rule, young children are able to derive unknown combinations of numbers from known combinations. For example, if a child is asked how much is 8 and 5, he can reason that 8 and 4 is 12, so 8 and 5 must be 13 because 5 is one more than 4.

Some children can add larger numbers (even up to three or four digits) by breaking them into hundreds, tens, and ones. For example, 123 plus 155 is 278 because 100 and 100 is 200 and 50 and 20 is 70 and 5 and 3 is 8. This kind of calculation clearly reflects an intuitive notion of place value, although the order of calculating digits reverses the direction mandated by the conventional written algorithms.

Different children prefer different strategies. For example, some may rely heavily on knowledge of doubles (i.e., 6 plus 6) to find new combinations. Some work with 10 and its multiples as jumping off points for mental calculation. Still others can use analogous concepts such as the relationship of coins to dollars to deal with decimals and fractions. Whatever the strategy, simple or complex, children's natural inclination to engage in sensible mental arithmetic should not be overlooked in school curriculums.

Instruction

There are several ways to use calculation to teach arithmetic and, in particular, multiplication in schools. For instance:

- Begin instruction with small two-digit multiplication problems such as 12 × 23 or 11 × 43. This allows children to use simple and easily available multiplication facts and frees their "mental space" for creative calculation. In this situation, most children can easily recall the small number facts and at the same time reason and manipulate key portions of the problem.
- Give children as much time as needed for each problem, allowing them to work at their own pace without actually telling them what to do. After solutions are obtained, ask the children to explain how they got their answers.
- If children seem to be having more difficulty than seems reasonable with any particular problem, try giving a small clue about a possible solution approach. For example, if the problem 12 × 23 seems to be difficult to manage because children may be trying to add 12 23 times, it might be useful to ask how the problem could be done if the tens multiplication part were to be done separately from the ones multiplication part.
- Provide problems with larger numbers using the above strategy of breaking the number into separate parts and then multiplying.
- If children tend to overuse one strategy, give them small clues about new approaches. For example, younger children working on small addition or subtraction problems often begin with a larger known combination and work backward (i.e., subtracting) to derive the answer to the current problem. For example, a young child might say that 12 plus 9 is 21 because 12 plus 10 is 22 and 9 is one less than 10 so you take away 1 from 22. Suggest a similar technique for multiplication. For example, in the problem 18 × 21, suggest that children begin by multiplying 21 by 20 instead of 18. Once the answer 420 is obtained, children can then be lead to focus attention on the difference between 18 and 20 (i.e., 2) and to use that number to figure out the difference between the products of 18 times 21 and 20 times 21. Once that answer is obtained (i.e., 2 × 21 = 42), it is a small step to figuring out what to do with the two answers (i.e., 420 and 42). The idea of subtracting (420 − 42 = 378) is likely to occur.

These are just a few of the many approaches that can be used to encourage children to work with mental arithmetic. The focus here is generally on using the natural mental-calculation strategies younger children use on single digit addition and subtraction problems. Without providing direct instruction, but by asking leading questions, it is possible to stimulate children's own thinking in directions that will make numbers sensible and manageable. The role of the teacher then is to guide children so that they choose to use on complex problems those sensible mental strategies originally invented for use on small, simple problems. A key component in learning to use mental calculation, therefore, is knowing when and how to apply the skills and knowledge already developed in other contexts. This component is critical to the development of mathematical thinking in general.

How does training in mental calculation benefit school mathematics? One benefit is practical: Having developed basic mental calculation skills, children quickly check written calculations in school. More importantly, children can learn that computation should make sense. With help, they can understand that the principles underlying mental arithmetic also provide the conceptual basis for the written algorithms learned in school; the latter can make sense too (and used properly are even more precise and reliable than the former). Most importantly, through the learning of mental arithmetic, children come to value and enjoy mathematical thinking and abandon an obsession with getting the correct answer.

Using Manipulatives to Connect the Concrete and the Abstract

In recent years, cognitive and educational theorists and educational practitioners have taken the position that manipulative materials can be effective in teaching arithmetic by explaining formal mathematics in terms of children's intuitive concepts and strategies. They allow children to use counting, engage in active learning, and observe concepts concretely represented. It is assumed that experiences with manipulatives will prevent children from blindly applying conventional algorithms and thus reduce the number of procedural errors.

Research shows, however, that children do not necessarily transfer to written problems the conceptual knowledge gained from work with manipulatives (Resnick and Omanson 1986, Leinhardt 1987). Rather, children may develop separate and unrelated systems of knowledge corresponding to each type of instruction. They accurately and sensibly manipulate rods or blocks to solve arithmetic problems, but at the same time may exhibit classic procedural errors in dealing with written calculation of the same type. It is clear that knowledge of a particular arithmetic operation or principal connected with manipulatives does not necessarily or automatically transfer to written forms of the same operation or principal. One of our educational goals, therefore, should be to bridge the gap between what is learned from manipulatives and what is learned from written, symbolic materials. We need to develop connections between the concrete and abstract forms of representing mathematical concepts and procedures (Heddens 1986).

Psychological Background

One source of this gap between concrete and symbolic knowledge is the fact that different manipulatives represent the same mathematical concepts and procedures in fundamentally different ways, and written symbols may represent these concepts and procedures in still other ways.

For example, the calculation 102 − 53 can be represented by beginning with a set of 102 chips, removing 53, and counting what is left to get the answer, 49. Once the 53 is removed, the 102 is no longer visible: All that remains to be seen is the difference, 49. Alternatively, the problem may be represented on a balance scale so that one side is weighted with pieces representing 102 and the other side is weighted with pieces representing 53. The solution is then obtained by adding more weights to the lighter side until both sides are balanced. The number needed to balance the scale in this case of course will be 49.

The focus of this representation is on the relationship between addition and subtraction, and the process used for solution is essentially addition. Written calculation offers a third way of looking at this seemingly simple problem. In the standard algorithm, both the smaller and larger numbers appear on the page at the same time. During the subtraction procedure, and even after the answer is obtained, the smaller number does not disappear, but remains continually visible.

We see then that the operations on the numbers in the two manipulative forms of representation, therefore, are not identical to one another, nor is either one identical in structure to the operation of subtraction done with the standard regrouping algorithm. These differences in meaning and ways of manipulating numbers sometimes can lead to confusion rather than clarification. A child competent in the use of one manipulative material may at the same time misuse written algorithms. Conversely, a child skilled in executing algorithms may have difficulty representing the same problem with a manipulative.

Adding to these difficulties is the fact that different kinds of manipulatives are often used for instruction in different operations. For example, chip trading (a method in which different colored chips are used to represent numbers in the units, tens, hundreds places, and in which 10 units pieces can be traded for one tens piece, etc.) is often considered ideal for teaching subtraction of whole numbers with regrouping, but plastic rods of varying lengths may be preferred for subtraction with fractions. This may lead again to the development of different systems for interpreting mathematical information. Under these circumstances, children may fail to make connections among the same arithmetic operations in whole numbers, fractions, and probably decimals as well. If manipulatives are to be successfully integrated into the curriculum, we must carefully examine the ways they represent the underlying mathematical concepts.

Instruction

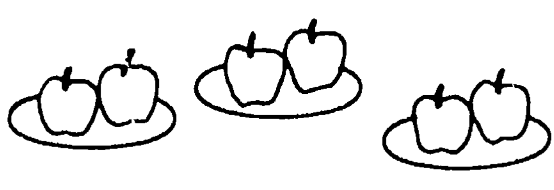
To see how manipulative materials can reinforce the connection between concrete and symbolic representations, let us consider a hypothetical lesson in which a simple form of manipulative material is used to teach multiplication with mixed numbers. The material, called a "tile" (although it can be made of cardboard or paper), was developed by the Japanese Association for Mathematics Instruction, but is similar to many other materials that represent numbers with rods or unit blocks (Easley 1983, Ginbayashi 1984). Of more interest than the particular material is the approach guiding its use. The goal of the lesson is to foster conceptual understanding of the operation of multiplication as it applies to calculation with whole numbers and fractions. Throughout the lesson the focus is on integrating procedural (how to calculate) and conceptual (why it works) knowledge.

The lesson begins with a simple problem in whole number multiplication. The purpose of beginning this way is to provide children with a basic mathematical structure that can later be used to interpret a fractions multiplication problem that looks quite different but is essentially the same. The teacher writes the problem 2 × 3 on the board and asks the students to give some specific examples from everyday life for the meaning of the 2 and of the 3. "The 2 could be apples and the 3 could be plates" is the kind of answer the teacher seeks. However, answers such as "the 2 can be apples and the 3 can be oranges" should be examined so that the children can better understand what does and does not make sense in looking at the multiplication relationship between the two numbers.

After taking suggestions for labeling the numbers with specific contents, the teacher might then ask the class to tell what the answer would be. Because this is such a simple problem, everyone will know that 2 × 3 is 6. The more difficult task is conceptualizing what the 6 represents. If, for example, the class chooses oranges and apples, what then is the meaning of the 6? After some discussion of this issue, the children should be able to understand that if the apple and orange kind of problem structure is employed, the 6 has no sensible mathematical meaning. The children will most likely conclude that the problem is best represented by some variation of 2 apples and 3 plates (i.e., three sets with two members in each set).

Given this conceptualization, both an overhead projector and worksheets are used to depict the problem with pictures of apples on plates, and with the conventional symbolism for multiplication (see Figure 4.1). The children are asked to count up all the objects in the picture that will give the answer 6. With no difficulty at all, the children should be able to choose and count all the apples. In this way, they can link the necessary operation (count the sets of apples repeatedly until all are included in the total) to the graphic and symbolic representations of the structure of the problem (2 apples on

Figure 4.1
Multiplication Analogy: Apples and Dishes



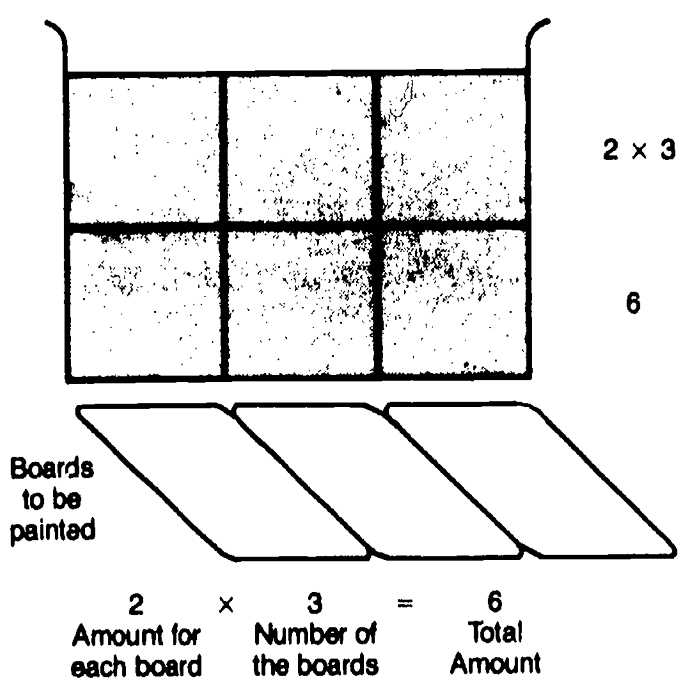
2	×	3	=	6
Amount for each dish		Number of the dishes		Total Amount

each of 3 plates is 6 apples). Thus, the structure of the multiplication operation is revealed as the action by which equal sized groups are combined to produce a quantity that stands for the total number of objects involved, not the number of groups. This simple demonstration also provides an opportunity for children to make the operation meaningful by applying counting to relatively concrete examples, a key aspect of the informal system of mathematical understanding that children bring with them to school.

The same numerical example is then applied to a new situation. This situation, provided by the teacher, appears in the children's worksheets and is projected on a screen (see Figure 4.2). This time the problem is depicted so that the units are represented by the "tile" shape and described as follows:

> These squares (tiles) are cans of paint, and the other shapes are boards to be painted. It takes 2 (tiles) cans of paint to

Figure 4.2
Multiplication Analogy: Boards and Paint #1

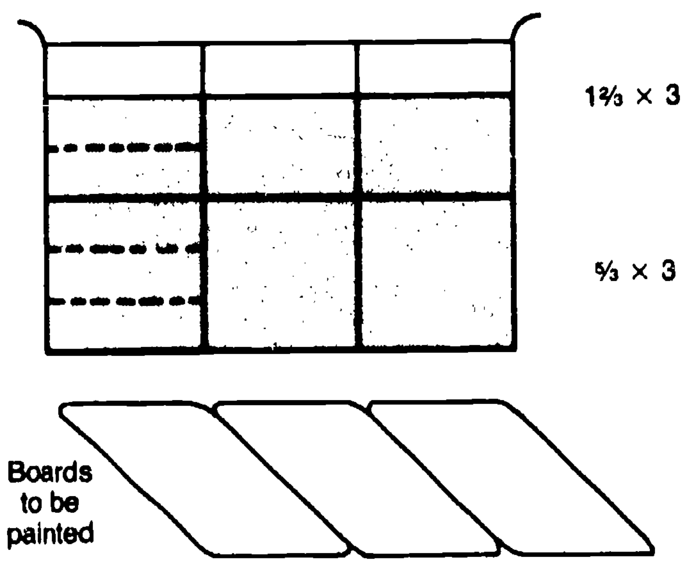


cover each board. There are 3 boards to paint. How many cans of paint (i.e., how many tiles) are needed?

From the diagram, the children easily can see and can count 6 cans of paint in all. The relationship of this situation to the written $2 \times 3 = 6$ problem is discussed, again focusing on what the 2, the 3, and the 6 represent. Each of the cans of paint is then described as a tile and a model of a single tile is shown next to the paint squares. This is to make it clear to the students that the particular size square stands for one unit or one whole.

Following this discussion, the teacher presents the paint problem with a variation: the painter wants to save paint and has figured out that he only needs $1\frac{2}{3}$ cans of paint to paint each board. The new problem is also pictured on the worksheets (as tiles) and projected on a screen (see Figure 4.3). The question is to figure out a way to represent the problem with symbols. The students are reminded to use the original 2×3 problem to help them out. In the process, the teacher again reviews what each of the numbers represents so that

Figure 4.3
Multiplication Analogy: Boards and Paint #2



the children will be likely to grasp that the new problem can be represented symbolically by $1\frac{2}{3} \times 3$ where the $1\frac{2}{3}$ stands for cans of paint and the 3 stands for boards.

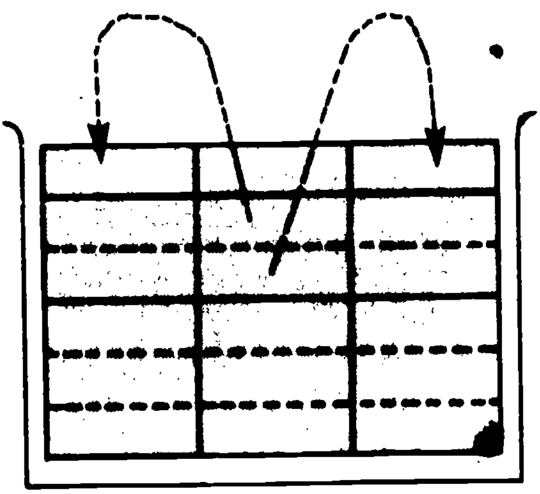
Next the teacher may want to draw the students' attention to non-algorithmic ways of determining how many cans of paint (tiles) will be needed to paint the 3 boards (for example by counting the appropriate tile sections in the diagram). The teacher discusses whether the painter will now need more or less paint than when the boards were painted with 2 cans. This is intended to help the children make sense of the meaning of the mixed fraction by comparing it with whole numbers. At this point, the process does not involve talking about converting the mixed number to a fraction and does not involve talking about how the 3 can also be written as a fraction (i.e., $\frac{3}{1}$). Instead, the idea is to reinforce the notion of the numbers as representing real quantities, in this case paint (tiles), and to use the symbols as convenient ways of expressing those quantities. This approach prevents the symbols from becoming the primary referents in the child's conception of fractions and mixed numbers.

Before coming to the final solution for the problem, (i.e., counting the paint [tile] units and fractional parts of paint [tile] units, the children are asked about what the fractional parts of the cans of paint represent (i.e., $\frac{1}{3}$ of a pint [tile], $\frac{2}{3}$ of a pint [tile], etc.) They are asked to define the $\frac{2}{3}$ cans in a new way, in terms of the $\frac{1}{3}$ sections of the paint (tile) units. Some children may immediately suggest that the 5 sections are called $\frac{5}{6}$ because from habit they assume that seeing any quantity divided into 6 sections means that sixths are being discussed. The teacher then can question the children so that they are reminded that each paint (or tile) unit represents one whole thing and that the six sections represent two whole things. By referring back to the tile unit as a model, children can conveniently keep in mind the concept of one whole unit divided into sections of thirds and by extension two whole units each divided into thirds, as represented in the pictures. The children then are able to count the fractional parts of the two cans of paint as five thirds, which is then represented symbolically by the teacher as $\frac{5}{3}$.

Once these graphic and symbolic connections have been made, the question can be asked about how much paint will be needed in total if the three boards are each to be painted with $1\frac{2}{3}$ cans of paint. The solution is determined by counting the cans of paint (tiles). First, the three whole cans are counted and then, through the use of arrows, one of the thirds from the middle section of the diagram is moved to the left portion of the diagram in order to make another whole pint of paint (i.e., $\frac{2}{3}$ of a pint and $\frac{1}{3}$ of a pint make one whole pint of paint). Similarly the same procedure is enacted for the section on the right side of the diagram (see Figure 4.4). In this way the children can see that there are 5 whole cans of paint used in the problem: $1\frac{2}{3}$ cans of paint times 3 boards. This procedure, of course, can be carried out by cutting the tile units into thirds and recombining them instead of just referring to the picture with the arrows.

This kind of solution process, gone over carefully and slowly for a few key problems, can become the conceptual basis for the later learning algorithm for multiplication of mixed numbers. Through this type of procedure children can develop a concrete visual referent from the image of moving fractional parts from one section to another to make more whole cans of paint. This provides them with a solid foundation for understanding how the operation works. In addition, because the written symbols are introduced with graphic representations, they become linked to something "real." When children are taught in this way, through manipulative materials, the concrete representation provides a vivid mental impression and serves as a referent for later mathematics learning. The power of these impressions comes from their connection to the kind of mathematics that

Figure 4.4
Boards and Paint Analogy:
Partitioning and Rearrangement



$\frac{5 \times 3}{3}$ See how many $\frac{1}{3}$ are in total

$\frac{15}{3}$ 15 of $\frac{1}{3}$ are found

5 5 One Tiles (squares) can be made up by 15 of $\frac{1}{3}$

makes sense to children and is rooted in their natural view of the world. For children, these connections to the concrete world result in an effective transition to a conceptual understanding of symbolic algorithmic procedures.

Summary

Mathematics curriculums and children's interpretive efforts interact to shape the learning process. This interaction is seldom noticed when the curriculum and the ways children make sense of it are in harmony. However, children's ways of looking at the world and the ways in which material is presented are often at odds, and this mismatch can lead to poor learning.

To avoid this, mathematics should be taught in ways that take into account the natural intuitions and intellectual constructions children use to interpret the curriculum. The examples provided illustrate only a few possible materials and techniques for bringing the psychology of children's mathematical thinking into the classroom. Many other areas of mathematics can profit from this approach, such as geometry, measurement, probability, and algebra. Whatever the content area, the general goal of instruction should be to encourage activities that build on children's own constructions of mathematical relationships.

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5

Teaching Mathematical Thinking and Problem Solving

Alan H. Schoenfeld

In his classic monograph *Productive Thinking* (1945/1959), Max Wertheimer illustrated what was in the 1940s—and what will be in the 1990s—the fundamental issue regarding teaching mathematical thinking and problem solving. He asked children to perform arithmetic operations like the following:

$$\frac{274 + 274 + 274 + 274 + 274}{5} = ?$$

Wertheimer (p. 130) reported "clear-cut results with some bright subjects. Most of them laughed, enjoyed the joke, while others were puzzled that such an easy problem should be given, or were bored; but they had no difficulty with the answer." These students realized, of course, that there is no work to be done: The repeated addition in the numerator is equivalent to multiplying by 5, an operation that is undone by the division in the denominator. To Wertheimer's surprise,

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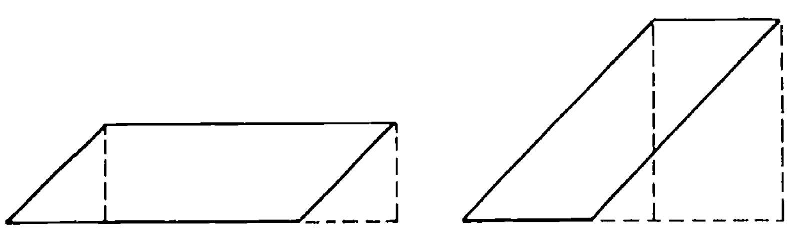
however, "a number of children who were especially good in arithmetic in their school were entirely blind, started at once with tedious figuring." They laboriously added the terms in the numerator, and then carefully divided the sum by 5. On the one hand, we can say that these students had learned their lessons: They could perform the arithmetic algorithms flawlessly. On the other hand, they missed the point of the example altogether.

Another of Wertheimer's examples, the "parallelogram problem," documents a similar phenomenon. Wertheimer watched a teacher prove to a geometry class that the area of a parallelogram is equal to the product of the lengths of its base and altitude. (The diagram that typically accompanies the proof is given in Figure 5.1a.) The addition of the dotted lines to the parallelogram shows that it can be rearranged into a rectangle whose area is easily calculated. The teacher lectured clearly on the proof, drilled the students on lots of numerical examples, gave them similar homework problems, and had students come to the board to repeat the proof. Everything went smoothly, and the students did quite well on a quiz.

As Wertheimer notes, most people would consider this an excellent class. Yet he had the feeling something was missing. With the teacher's permission, he asked the students a question about a par-

Figure 5.1
Parallelogram Problem

Students who had merely memorized the procedures could answer all the teacher's questions about Figure 5.3a, but were stymied when asked about Figure 5.1b.



a. A parallelogram in standard position. With the appropriate construction lines, it becomes clear that the parallelogram can be rearranged into a rectangle.

b. Wertheimer's parallelogram, in nonstandard position. If you copy the construction lines from Figure 5.1a, the result is confusing.

allelogram presented at a different angle (Figure 5.1b) from the generic parallelograms the students had worked with. Confronted with this new problem, one student flatly stated, "We haven't had that yet," and would go no further. Others rotely repeated the procedures of the proof and were stymied when it didn't work the same way. (Adding vertical and horizontal construction lines similar to those in Figure 5.1a results in Figure 5.1b, which is rather confusing.) Yet Wertheimer's problem was exactly the same as the ones given by the teacher. The parallelogram in Figure 5.1b, like the one in Figure 5.1a, can easily be cut up and reassembled into a rectangle. To do so, however, you have to focus on the properties of the parallelogram rather than on the steps of the solution itself—which were the focus of the classroom discussion and what the students had memorized.

Wertheimer stressed that although the students had "mastered" the relevant facts and procedures—addition and division in the first example, a proof procedure in the second—they had, in a significant and critically important way, failed to understand the ideas behind the procedures. Mastery of the procedures was important, but it was also sterile. The power that lies in learning mathematics, according to Wertheimer, is the ability to use it. If students can only employ a procedure blindly or can only use a technique in circumstances precisely like those in which they have been taught, then schooling has in large part failed them.

Half a century after Wertheimer wrote *Productive Thinking*, his argument has even more force. For the most part, students' mathematical learning seems the same as the kind Wertheimer deplored. The world has changed in important ways, but our classrooms do not fully reflect those changes. For example, the presence of computational technology (i.e., computers and increasingly powerful hand-held calculators) has significantly decreased the need to spend classroom time mastering some of the paper-and-pencil algorithms that were once considered necessary for competent arithmetic performance. Cheap and readily accessible calculators perform all of the basic arithmetic operations. According to the Mathematical Sciences Education Board's (MSEB) Curriculum Framework Task Force (March 1988), the ability to perform paper-and-pencil algorithms should no longer be considered a curricular prerequisite for problem-solving activities in grades K-6. Rather, MSEB suggests the emphasis in instruction should be shifted to the development of "number sense." Number sense includes possessing:

- **representational abilities:** skills with whole numbers, rational numbers, and decimals, and an understanding of place value.

● **numerical operations skills:** mastery of single-digit operations and the ability to identify the "right" arithmetic procedures for various problem situations, to select the appropriate means for carrying them out (mental arithmetic or calculator use), and to perform estimations.

● **interpretation skills:** being able to draw inferences from numerical data.

MSEB also notes that a new breed of hand-held calculator, exemplified by the Hewlett-Packard HP-28C, both performs symbol manipulations and can graph relatively complicated functions. (It can determine the algebraic product of the expression $[2a+b][3a+5b^2]$, for example, and differentiate the result with regard to either a or b. It can also graph the functions $y = \cos x$ and $y = 2x$, and solve the equation $\cos x = 2x$, by "homing in" on the points of intersection graphically.)

One can expect the next generation of such machines, available by the mid-1990s, to be more powerful, relatively cheap (under $50), and widely accessible—as accessible as slide rules were for secondary school students 30 years ago. These calculators will enable secondary school students to tackle substantial applications, modeling, and statistical problems without being hampered by the inability to carry out complex or time-consuming calculations. In short, computational devices such as calculators and computers can make more classroom time available for discussions of mathematical substance. They can be used as tools to help students understand problematic situations through mathematical analysis. That end is increasingly important as we become more of an "information society" and jobs require increased technological (and inherently mathematical) sophistication. Borrowing once again from the MSEB Task Force report, we take for mathematics instruction, in particular for problem-solving instruction, the following major goal:

> Mathematics education must focus on the development of *mathematical power*, by which is meant the development of the abilities to:
>
> - understand mathematical concepts and methods;
> - discern mathematical relations;
> - reason logically; and
> - apply mathematical concepts, methods, and relations
>
> to solve a variety of non-routine problems. (MSEB 1988, p. 34)

Before elaborating on these ideas, I note that there are strong analogies between competent performance in mathematics and competent performance in reading and writing. Traditional aspects of the mathem·.ics curriculum (e.g., mastering computational skills) comprise some of the basics of mathematics instruction, just as decoding skills comprise some of the basics for reading and grammatical skills for writing. In mathematics, the basics have at times in essence been the curriculum (e.g., the 1970s "back-to-basics" movement). But such a curriculum cannot do justice to the idea of mathematical power. One cannot learn to read, of course, without learning to decode words. But, the chapters by Beck and Palincsar and Brown in this volume make clear that decoding skills are a small subset of the tools possessed by skilled readers. Skilled readers also have strategies for understanding, summarizing, and predicting. They have metacognitive skills to monitor their own understanding and make sure they are getting what they should from the readings. And they even have a certain sense of themselves as readers and what reading is all about. Similarly, Hull's chapter in this volume starts with the premise that writing is about communication and ideas, not grammar. You can't write well, of course, without grammar. It has to come as easily to the writer as the basic number facts must come to the person who frequently uses arithmetic. But there is much more. Good writers have strategies to convey meaning and make sure the reader gets the point (e.g., using topic sentences). They have strong metacognitive skills (e.g., the ability to place themselves in the position of the reader and see if the message is getting across). And they too have a certain sense of what writing is all about (conveying ideas, engaging the reader) and of their membership in a community of writers.

This chapter outlines the parallels for mathematics. I do not discuss the basics, but problem-solving strategies—what they are, and what kinds of classroom situations are conducive to developing them—receive a lengthy treatment. This discussion is followed by the consideration of metacognitive issues in mathematical problem solving, and a concluding discussion of what it means to develop a "mathematical point of view."

Problem-Solving Strategies

Let me begin with a definition. For any student, a mathematical *problem* is a task (a) in which the student is interested and engaged and for which he wishes to obtain a resolution, and (b) for which the student does not have a readily accessible mathematical means by which to achieve that resolution.

As simple as this definition may seem, it has some significant consequences. First, it presumes that engagement is important in problem solving; a task isn't a problem for you until you've made it *your* problem. Second, it implies that tasks are not "problems" in and of themselves; whether or not a task is a problem for you depends on what you know. Third, most of the textbook and homework "problems" assigned to students are not problems according to this definition, but exercises. In most textbooks, the majority of practice tasks can be solved by the direct application of a procedure illustrated in the chapter—e.g., solving a quadratic equation after you have been taught the quadratic formula, or a "moving trains" problem when the text has illustrated the specific procedures for solving "distance-rate-time" problems. In contrast, real problem solving confronts individuals with a difficulty. They know where they are, and where they want to get—but they have no ready means of getting there. Fourth, the majority of what has been called "problem solving" in the past decade—introducing "word problems" into the curriculum—is only a small part of problem solving. (Having students solve worksheet after worksheet of tasks like "John had seven apples. He gave four apples to Mary. How many does John have left?" can be as mind-numbing as having them solve sheet after sheet of problems like "$9 - X = 4$," especially if the students use procedures like the "key word" method to answer the problems without trying to understand their content. Word problems are not an end in themselves but a means of developing mathematical power.) And fifth, as broad as the definition above may seem, *problem solving* covers only part of "thinking mathematically." Also important are developing metacognitive skills and developing a mathematical point of view (see below). Let's consider two examples and the generalities behind the specifics.

A First Example

> In a warehouse you get a 20 percent discount on all items but must pay a 15 percent sales tax. Which would you prefer to have calculated first: the discount or the tax?

This is the first problem in Mason, Burton, and Stacey's (1982) book *Thinking Mathematically*. If readers don't know the answer, they are invited to make the relevant computations for an easy number, say \$100. "Surprised by the result? Most people are, and it is that surprise which fuels mathematical thinking. Now, will the same thing happen for a price of say \$120?" (p. 1)

Once readers make the relevant conjecture (that the order of tax and discount doesn't matter), they are encouraged to figure out why—by thinking of a 20 percent discount as equivalent to paying 80 percent of the full price, or multiplying the price by 0.8. After some work to compute the final cost, we see that if the price of an item is P dollars, taking the discount and then the tax amounts to computing (1.15)[(.8)(P)] dollars, while computing the tax first gives a total of (.8)[(1.15)(P)] dollars. Since (1.15)(.8) = .92 = (.8)(1.15), you get the same amount in either case. Readers are then invited to see if there is anything special about the tax and discount rates, and they are led to the discovery (and algebraic confirmation of the result) that no matter what the tax and discount rates, you can take them in either order.

In this example the authors were hampered by the need to present the problem discussion in text form; they are, of course, more flexible in establishing classroom dynamics for the problem discussion. But even so, note the way the problem was posed. The answer could have been (and typically would be) given as the problem statement, "Show that it doesn't matter whether you compute the discount or the tax first." But it wasn't; rather, it was left for the reader to discover. When the problem is used in classroom discussions, John Mason breaks the class into small groups, and each group determines which examples to pursue. Sometimes this leads to the chain of reasoning described above, sometimes to other arguments. (One group, for example, tried the problem for $100, $200, and $300, and noticed that the total cost is proportional to the cost per $100; the group did the computation for $1, and argued that every cost is a multiple of the cost per $1.) In both the text and the book, Mason highlights the strategies students are induced to use, for example, "specializing" (choosing particular values such as $100) and "generalizing" (moving to any discount and any tax). When the class works in small groups, students try to convince each other. Then, when the groups compare and contrast their results, they work to convince each other that their answers are correct. Working with the ideas generated by the class, Mason helps the students to develop standards by which arguments will be considered (first convince yourself, then a friend, then an opponent).

A Second Example

At one level, the next problem is trivial. Most people can solve it by trial and error in 10 or 15 minutes. Yet the problem and its extensions can occupy students fruitfully for a week, and related problems have occupied mathematicians for years.

Consider Figure 5.2. The problem is to place the digits 1 through 9 in the boxes so the sum of the numbers along each row, column, and diagonal is the same. The completed box is called a "magic square."

One solution goes like this. First, what extra information would help? The problem would be much easier if we knew the sum of the rows, columns, and diagonals. (Finding such stepping stones to a solution is called "establishing subgoals.") There is a classical kind of mathematical thinking that helps determine the sum: Assume there is a solution and determine the properties it must have.

In this case, the sum of the first column—say S—would be the same as the sum of the second and the sum of the third columns, so the sums of the 3 columns would be 3S. Adding up the three columns gives you $1+2+3+4+5+6+7+8+9$, which is 45. So $3S = 45$, and $S = 15$ (see Figure 5.3).

Continuing from this point, the next major subgoal might be to determine which digit goes in the center. Could it be 9? Now that the

Figure 5.2
The Magic Square Problem

Can you place the digits 1, 2, 3, 4, 5, 6, 7, 8, and 9 in the box so that the sum of the digits along each row, each column, and each diagonal is the same? (The completed box is called "magic square.")

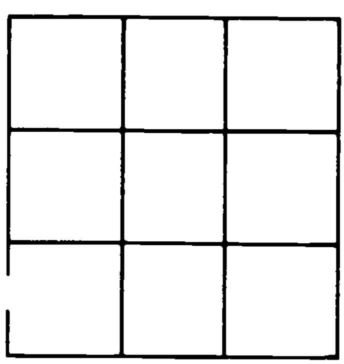
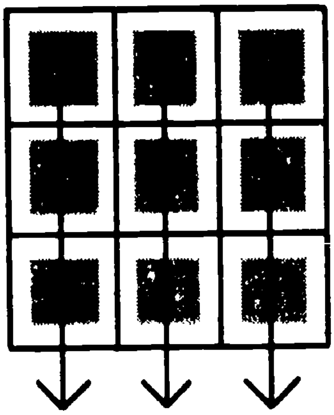


Figure 5.3
Determining the Sum of Each Column



Assume the square has been filled in. Adding up vertically, each column gives the sum S. But all together the three rows go through each box in the magic square; hence each digit from 1 through 9 is counted once.

$$S + S + S = 1 + 2 + 3 + 4 + 5 + 6 + 7 + 8 + 9$$
$$3S = 45, \text{ so } S = 15.$$

sum is known to be 15, 9 can't possibly work: With 9 in the center, one of the sums would involve an 8 and a 9. That would add up to 17, which is too large. Similarly 8,7, and 6 can be ruled out; each of them would if in the center, be included in a sum with the 9. (This strategy, first considering an unlikely candidate, is called "examining extreme cases." It's frequently a useful technique.) Likewise, 1 can't go in the center; it would be in some row (or column, or diagonal) with 2, and then you would need a 12 to add up to a total of 15. The digits 2, 3, and 4 can be eliminated the same way. That leaves 5. With 5 in the center, we can begin trial-and-error. But the trial-and-error doesn't have to be random—and there doesn't have to be very much of it. If there is a solution with (say) the digit 1 in the upper left-hand corner, then by rotating it 90 degrees clockwise we obtain a solution with a 1 in the upper-right corner. Two more rotations produce solutions in the other two corners. Hence, a solution with a particular digit in any one corner is equivalent to solutions with that digit in any other corner. We only need to consider potential solutions that focus on different digits in the upper left-hand corner. (This is called "exploiting symmetry.")

From this point on, a small amount of experimentation yields a solution, which I will leave for you to discover. When my students find an answer, I ask them if we're done and ready to move on to the next problem. They always say "yes;" after all, the goal is to get the answer, isn't it?

No, it isn't. The goal is to understand the magic square, and at this point in the solution that process has just begun. Students will understand the square better if they can re-solve the problem in a different way. There is an interesting "working backwards" solution, which goes as follows. If we had a complete solution, there would be a lot of triples of numbers that add up to 15. Why not list those, and see what the set of candidate triples might be? After some experimenting (and this is an opportunity for the teacher to suggest that the students be systematic), the students will generate the following as the only triples of digits that add up to 15:

$$(1,5,9), (1,6,8), (2,4,9), (2,5,8),$$

$$(2,6,7), (3,4,8), (3,5,7), (4,5,6).$$

I noted earlier that the center square is the most important in the magic square: It's involved in four sums. How many of the digits from 1 to 9 appear in four different triples on our list? Only the 5 does, so it must go in the center. Moreover, the even digits all appear three times (they can go in corners), and 1,3,7, and 9 each appear only twice (they will have to go in the side slots). The numbers can now be plugged in without trial and error. An important mathematical lesson has been learned: There's more than one way to solve a problem. But this is just the beginning, because the problem solved was my problem rather than my class'. Extensions and generalizations generated by my classes have included:

- Can you get a magic square with the numbers 2,3, . . .,10?
- With 37,38, . . .,46?
- With 5,10,15,20, . . .,45?
- With 7, 12, 17, 22, . . .,47?
- The "magic number" for this square was 15. Is there a magic square with a magic number of 75? 76?
- Can you develop a procedure for generating all 3×3 magic squares? What can we say about 4×4's? 5×5's?

By the time they reach this point the students are no longer working my problem; they are exploring their own. In short, they are doing mathematics. But we should not slight the first problem, for it is quite rich. Simple as it may seem, it is a springboard for discussion (and amplification) of the following important mathematical ideas: establishing subgoals, working forwards, working backwards, assuming you have a solution and determining its properties, exploiting extreme cases, exploiting symmetry, solving problems in more than one way, generalizing, and creating one's own problems.

Discussion

These two examples are the tip of the iceberg. There are, of course, numerous other problem-solving strategies in the Pólya tradition (see Polya 1945, 1981). For descriptions see Mason et al. (1982), National Council of Teachers of Mathematics (1980), Joint Matriculation Board (1984), Schoenfeld (1985, 1987), Silver (1985), Stacey and Groves (1985). I have tried to focus on the style of the problem sessions as well as their content, because the atmosphere in which students learn the strategies is critically important. Here is Stacey and Groves' summary of the teacher's role in problem-solving instruction:

> It is up to the teacher to
>
> - help children accept the challenges: a problem is not a problem until you want to solve it.
> - build a supportive classroom atmosphere in which children will be prepared to tackle the unfamiliar and not feel too threatened when they become stuck.
> - allow children to pursue their own paths towards a solution and assist them when necessary, without giving the answers away.
> - provide a framework within which children can reflect on (i.e., think about, discuss, and write about) the processes involved and thereby learn from experience.
> - talk to the children about the processes involved in doing and using mathematics, so that they can build up a vocabulary for thinking and learning about it. Children learn much more effectively when the teacher draws their attention explicitly to the strategies and processes involved. (1985, p. 5)

There is ample documentation for the points summarized here, and for the fact that in supportive environments students do master the kinds of problem-solving techniques discussed above (including evidence of transfer, where students solve essentially novel problems using the techniques they have studied in a problem-solving course); see the references cited in the previous paragraph for details on classroom implementation, and Schoenfeld (1985, 1987) and Silver

(1985, 1987) for details on the research. I note in closing this section that there might be some concern that the focus has not been on standard classroom material. Here are some brief responses to that concern.

First, observe that the problems provide an opportunity for review and consolidation of important mathematical ideas (e.g., the commutativity of multiplication in the first problem, the use of variables in the second) as well as a focus on problem-solving processes. Second, these problems are not that unusual. Many standard exercises can be converted into more interesting problems by changing the phrasing from "Show that . . ." to "A friend of mine claims that. . . . Is she right?" Thus, we can present standard subject matter in a more problem-based fashion (see Butts 1980). Third, problems can be an introduction to seeing mathematical connections and gaining an understanding of mathematical concepts (see the discussion of Lampert's work below). And fourth, the goal here is to help students develop "mathematical power" as described above. From that point of view, becoming able to solve problems such as these is not an "extra" or a recreation, but a central skill in learning to use mathematical ideas. (Note, indeed, that the approach taken here works just as well for regular curricular material as it does for recreational mathematics. The Pythagorean theorem and its extensions can be explored in the same way that I explored the magic square.)

Metacognition and Self-regulation

Broadly speaking, metacognition refers to people's understandings about their own thought processes. The term entered the psychological literature in the late 1970s, although it has a long and distinguished heritage in both philosophy and psychology. The aspect of metacognition of concern here is often referred to as "self-regulation." For example, as you read through a text, there may come a point where you stop and say, "I'm not understanding this as well as I should. I'd better reread it, and think about it until I've made more sense of it." As you are writing, you may be in the midst of a paragraph when it strikes you that you've gone off track: The paragraph isn't saying what you wanted to say, and you should either change your plan (if the writing was leading you in interesting directions) or scrap parts of it and start over. Or, as you are working a complex mathematical problem, it may occur to you that the problem is more difficult than you had thought; you had better spend some more time trying to understand it, or abandon your current approach for another. Despite the differences in domains (reading, writing, and mathematics), you have done much the same thing in each case. While engaged in a task of some intellectual complexity, you have evaluated the current state of affairs and decided to do something about it. (Or, you may feel that things are going just fine, in which case it is appropriate to continue without interruption.) Keeping tabs on your current state, and doing something different if warranted, are central aspects of self-regulation.

In general, cognitive research has pointed to the "domain-specificity" of subject-matter learning: The skills needed to learn the "basics" or particular problem-solving strategies in mathematics are different from those in chemistry, writing, or reading, and instructional techniques need to take account of the particulars of the domain. At the level of self-regulation, however, the issues appear to be the same across subject-matter boundaries. Are things going well as you perform a complex task? If yes, then leave well enough alone. If not, then there might be things you can do—and here, the details may be domain specific. (The reader will note strong similarities between the presentation here and the discussion of similar issues in the chapter by Palincsar and Brown.)

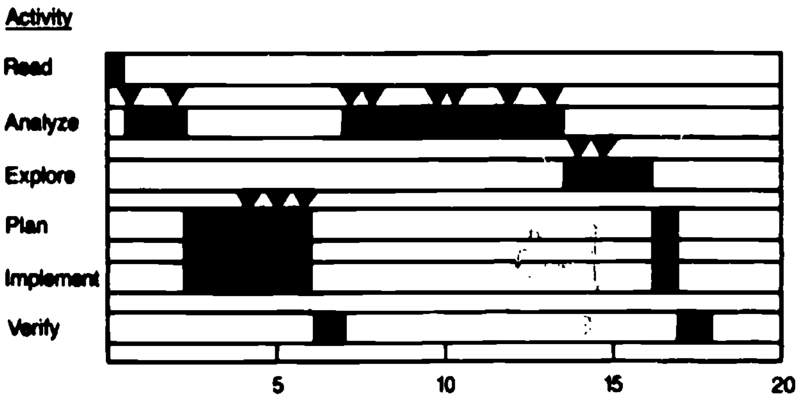
The story, in brief, is told in Figures 5.4 and 5.5.* Figure 5.4 shows the graph of a mathematics faculty member's attempt to solve a difficult two-part problem. The first thing to note in Figure 5.4 is that the mathematician spent more than half of his allotted time trying to make sense of the problem. Rather than committing himself to any particular direction, he did a significant amount of analyzing and (structured) exploring; he did not move into implementation until he was sure he was working in the right direction. Second, each of the small inverted triangles in Figure 5.5 represents an explicit comment on the state of his problem solution. For example, "Hmm. I don't know exactly where to start here" (followed by two minutes of analyzing the problem), or "OK. All I need to be able to do is [a particular technique] and I'm done" (followed by the straightforward implementation of his solution).

It is interesting that this faculty member had not worked in the subject domain, geometry, for 10 years. He had forgotten many of the standard results, and when he began working the problem, he

*Figures 5.4, 5.5, and 5.6 are modified from Schoenfeld (1985), which provides a more extended version of the issues discussed in this section.

Figure 5.4
Time-Line Graph

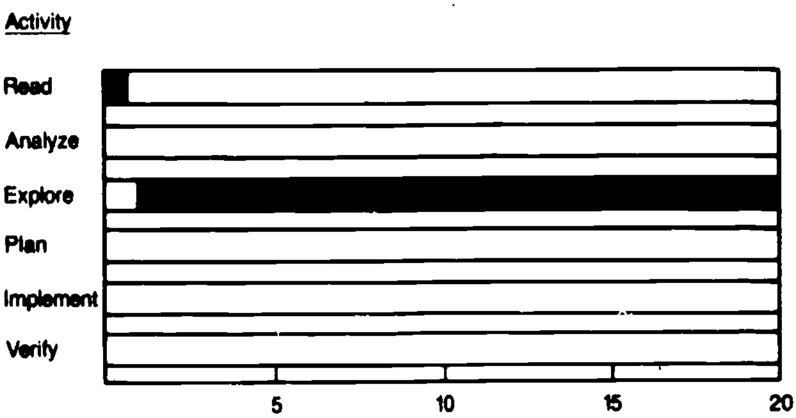
Mathematician Working on Difficult Problem



Elapsed Time (Minutes)

Figure 5.5
Time-Line Graph

Students Trying to Solve Non-Standard Problem



Elapsed Time (Minutes)

had fewer of the facts and procedures required to solve the problem than did many college students who worked the problem (since they had recently completed high school geometry courses). Moreover, in his solution attempt the mathematician generated a large number of potential wild-goose chases for himself. He didn't get deflected by them, however. By monitoring his solution with care—pursuing interesting leads, and abandoning paths that didn't seem to bear fruit—he managed to solve the problem, while the majority of students did not.

Figure 5.5, which is a stark contrast to Figure 5.4, presents a rather typical graph of a problem-solving attempt by two college students working as a team. These students read the problem, quickly chose an approach to it, and took off in that direction. They kept working in that direction, despite clear evidence that they were not making progress, for the full 20 minutes allocated for the problem session. (Note the absence of inverted black triangles, signifying that there was no "mid-term review" that would have illustrated difficulties with the approach or alternatives to be considered.) At the end of the 20 minutes, the students were asked how the approach they had taken would have helped them to solve the original problem. They couldn't say.

The reader may not have seen this kind of behavior too often. It does not generally appear when students work routine exercises, since the problem context in that case tells the students which techniques to use. (In a unit test on quadratic equations, for example, students know they'll be using the quadratic formula.) But when students are working on unfamiliar problems out of context, this behavior is more the norm. Examining more than 100 videotapes of college and high school students working unfamiliar problems, for example, revealed that slightly more than 60 percent of the solution attempts were "read, make a decision quickly, and pursue that direction come hell or high water." Note that a problem solver's first, quick, wrong decision, if not reconsidered and reversed, *guarantees* failure.

These two examples are relatively typical of expert and student behavior on unfamiliar problems. For the most part, students are unaware of or fail to use the metacognitive skills demonstrated by the expert. However, those skills can be learned as a result of explicit instruction that focuses on metacognitive aspects of mathematical thinking. That instruction takes the form of "coaching," with active interventions as students work on problems. (See Collins, Brown, and Newman in press for a general discussion of the issue.) Here is a brief description of an obtrusive but effective technique.

In my problem-solving courses, I frequently break the class into groups of three or four to work on problems while I circulate through the room as "roving consultant." As part of my consulting role, however, I reserve the right to ask the following three questions at any time:

> What (exactly) are you doing?
>> (Can you describe it precisely?)
>
> Why are you doing it?
>> (How does it fit into the solution?)
>
> How does it help you?
>> (What will you do with the outcome when you obtain it?)

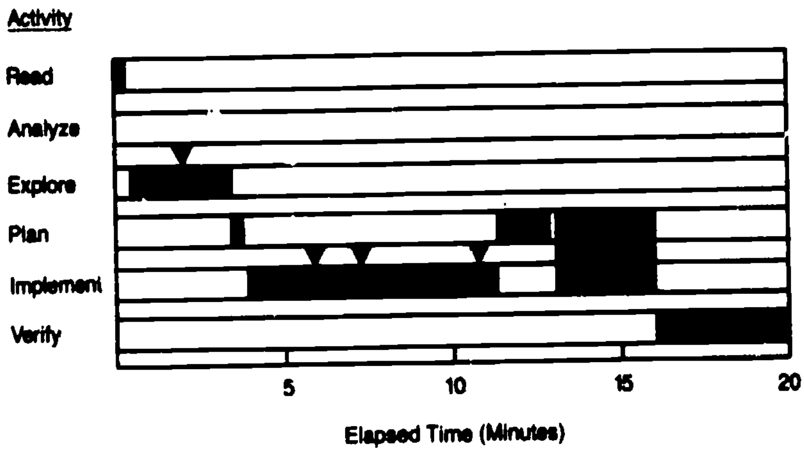
Students are asked these questions early in the term. They are generally at a loss to answer them (and I encounter a significant amount of hostility and resistance). When the students realize that the questions will continue, they begin to defend themselves by discussing the answers in advance. By the end of the term, discussing the questions has become habitual for them.

The results of these interventions are best illustrated in Figure 5.6, which summarizes how a pair of students solved a problem after a problem-solving course. After reading the problem, they jumped into one solution attempt that, unfortunately, was based on an unfounded assumption. They realized this a few minutes later, and decided to try something else. That choice too was bad, and they got involved in complicated computations that kept them occupied for eight and a half minutes. But at that point they stopped once again. One of the students said, "No, we aren't getting anything here. . . [What we're doing isn't justified]. . . Let's start all over and forget about this." They did, and soon found a solution.

The students' solution is not expert-like in the standard sense for two reasons. First, they rushed into explorations without careful analysis. (Old habits die hard, but note that they did extricate themselves from the hole the had begun to dig for themselves!) Second, they managed to find the "right" approach late in the problem session, after extended false starts. (Experts truncate the false starts more rapidly.) Yet in many ways, these students' work resembles the mathematician's behavior in Figure 5.5 far more than it resembles the typical student behavior in Figure 5.4. The point here is not that the students managed to solve the problem, for to a significant degree solving nonstandard problems is a matter of luck and prior knowledge. The point is that, by virtue of good self-regulation, the students

Figure 5.6
Time-Line Graph

Students Trying to Solve Problem after Problem-Solving Course



gave themselves the opportunity to solve the problem. They curtailed one possible wild-goose chase after beginning to work on the problem, and truncated extensive computations half-way through the solution. Had they failed to do so, they never would have had the opportunity to pursue the correct solution. In this, the students' behavior was expert-like, and in this, their solution was also typical of post-instruction work by students. After instruction, fewer than 20 percent of problem-solving attempts resembled "jump into a solution and pursue it no matter what." There was a concomitant increase in success in solving problems.

Developing a Mathematical Point of View

What is your response to the following problem?

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

If you are a typical adult reader, the odds are that you'll find it slightly funny—an obvious put-on. If, however, you were a typical school child given the problem in a school context, the odds are roughly three out of four that you would produce a numerical answer to the problem by combining the given numbers (Reusser 1986). In fact, the more you'd been exposed to mathematics in school, the more likely you would be to produce "answers," by combining numbers, to problems that didn't even ask any questions! Radatz (cited in Kilpatrick 1987) reports that when "problems" like the following:

> Mr. Lorenz and 3 colleagues started at Bielefeld at 9 a.m. and drove the 360 km to Frankfurt, with a rest stop of 30 minutes

are inserted into sets of exercises worked by school children, the percentage of students who "answer" them increases consistently from kindergarten through 6th grade. That is, children making their way through school are increasingly habituated to working routine, stereotyped exercises—to the point where they no longer ask that the situations described in the exercises be meaningful. The reductio ad absurdum of this lack of demand for meaningfulness was documented on the Third National Assessment of Educational Progress (Carpenter, Lindquist, Matthews, and Silver 1983), where a plurality of the students working an "applied" problem wrote that the number of buses required to transport a group of soldiers to an army base was "31 remainder 12."

Such apparently odd behavior has been conjectured (e.g., Carpenter et al. 1983, Reusser 1986, Schoenfeld in press) to be the direct, although unintended, consequence of current mathematics instruction. A case can be made that, despite the best of intentions, certain kinds of ritualized classroom procedures result in students' developing a skewed sense of what mathematics is all about. If students experience mathematics as a set of disconnected and (to them) arbitrary procedures passed on for their memorization, a substantial percentage will learn to use those procedures in a mechanistic way, without employing "sense checks" (such as seeing whether a "problem" really asks for an answer) or "reality checks" (such as noting that buses don't come with remainders).

Things need not be that way. Those who understand mathematics see it as a sense-making activity; they understand that much of mathematics was developed because of a need to solve problems, or because of pure intellectual curiosity. Those who appreciate mathematics generally come to experience it in that way. And there is a slowly growing literature indicating that mathematics can be taught in a problem-based way so students experience the subject as a discipline of reason where mathematical conventions and terminology make sense because they do work for you.

A recent example of this literature is Lampert (1988). Lampert constructed a sequence of lessons that were given to 5th graders in a public school. The goal was to have students develop an understanding of the rules of exponentiation: e.g., that (4×10^7) divided by (4×10^5) is 10^2. In particular, Lampert wanted her "students to learn not only that they could divide or multiply by subtracting or adding exponents, or how to use the technology of exponents, but also that the warrant for doing so comes from mathematical argument and not from a teacher or a book" (p. 17). Her lesson sequence began with a look at number patterns. She had students use calculators to construct tables of the squares from 1^2 to 100^2, and to see if they could make any predictions about the "last digits" of the numbers. At first arguing from the patterns and then more abstractly, the students argued that the last digit of the number being squared was the one that mattered in determining the last digit of the square. Then Lampert asked her students "What is the last digit in 5^4? 6^4? 7^4? and [she] challenged the class to tell [her] if they could prove that their conjectures about what these last digits would be were true without doing the full multiplications" (p. 20). This task led to a group discussion of the meaning of x^4, since agreement was essential for doing the problem solving task.

In discussing powers of 5, one student argued that 5^4—indeed, any power of five—must end in a 5 because it's just a product of 5's, and 5 times any number that ends in 5 must end in a 5. After substantial argument the class agreed with this conclusion and drew a similar conclusion about powers of 6; there was a conjecture that the same should hold for all digits from 1 through 9, but it was quickly refuted with the observation that 7^2 ends in a 9, not a 7. The class turned its attention to 7^4, which it dealt with by a general rule: In shorthand, x^4 is $(x^2)^2$, so the last digit of 7^4 is the last digit of $(7^2)^2$, or the last digit of $(49)^2$, which is the last digit of 9^2, or 1. Lampert then asked a key question: What is the last digit of 7^5? Multiple conjectures from the students led to significant argument among them, and ultimately to the realization that $7^5 = 7^4 \times 7^1 = 7^{4+1}$; further discussion about the last digits of 7^8 and 7^{16} led to more general discussion of the arithmetic of exponents. In sum, the arithmetic of exponents arose as a reasonable (and reasoned) way of dealing with mathematical problems that was meaningful to the students.

In different mathematical domains and at different grade levels, other mathematics educators have worked toward the development of similar sense-making practices in the classroom. Balacheff (1987), for example, has developed a sequence of lessons in which students discover, then conjecture, and then finally prove that the sum of the measures of the angles of a triangle is 180 degrees. In a classic work, Fawcett (1938) went one step further with high school students in a two-year geometry course. Fawcett never stated the results he expected students to prove (e.g., "Prove that the base angles of an isosceles triangle are equal"). Instead, he gave students various geometric figures to examine and asked them to say what properties they thought the figures had. These conjectures were the basis for classroom discussions (and ultimately proofs). Moreover, the argumentation procedures used by the class (induction, deduction, various logical forms of argument) were themselves the subject of discussion. In these classrooms, doing mathematics made sense. Mason and others (1982) approach mathematics with a similar spirit. In sum, there are instructional environments in which students come to see mathematical sense-making as something natural. The problem for us is to make such environments the norm rather than the exception.

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6
Research on Writing: Building a Cognitive and Social Understanding of Composing

Glynda Ann Hull

The Best and Worst of Times

For students who must learn to write in American schools, and for the teachers who must instruct them, it is the best of times and the worst of times. It is the best of times because we now know more than we ever have about the acquisition of written language, and we are learning still; because we are standing on the horizon of new technologies for communication that can put more information within the reach of more students and help them organize, synthesize, and interpret it; because we also have a strong and active grass-roots teacher movement with an aim no less modest than empowering those in the classroom. It is indeed the best of times for some students and teachers of writing.

For others, it is the worst of times. Despite our successes, there are young people who leave our schools with literacy skills too poor to gain them admission to regular courses in college, to fill out job applications, to analyze and deploy information, or to read stories to their children. We are warned that the situation will likely worsen as more and more children in American schools come from cultural traditions whose richness we've not yet learned to value and use to advantage in our classrooms.

In this chapter, I describe the kind of writing research that has the potential to make literacy classrooms inhabitable for more teachers and students—research based on an understanding of writing as a complex cognitive process embedded in a social context.

The Evolution of Our Concept of Writing

In the last 20 years, writing research and instruction have been turned on their heads.[1] We have learned to think differently about the nature of writing and the abilities of students and how we can best teach them to write (Figure 6.1). The rallying point of these revolutions has been the concept of writing as an activity, a process with an identifiable set of behaviors and cognitions. To think of writing as an activity, something that one does, is more commonsensical than surprising. But to think of writing as an activity that can be studied, analyzed, and understood, that can, in short, be demystified—this indeed is revolutionary, for it turns writing into something that can be acquired rather than something one either possesses or lacks. Educational practices in 19th century America are a good reminder of how important definitions are. In classrooms then, academic failure was believed to arise from faults of character or disposition. This is reflected in the tags educators used to pin on children who fell behind: "dunce," "shirker," "loafer," "reprobate," "wayward," "sluggish," or "incorrigible." As Cuban and Tyack (1988) point out, particular explanations generated particular solutions: Low achievers were segregated into remedial classes as befitted their presumably inferior intellects.

In like manner, textbooks for composition and grammar for a long time conjoined descriptions of "industrious," "hard-working" students with "good language" or "suitable compositions." The implication was that writing well was a natural consequence of being a good and moral person, and that writing poorly was a sign of depravity or sloth (Heath 1981). It is probably not coincidental, then,

[1]This history is necessarily brief and simplified to illustrate broad trends. For detailed accounts, see Braddock, Lloyd-Jones, and Schoer (1963); Cooper and Odell (1978); Hillocks (1986); and Freedman and Colleagues (1978).

Figure 6.1
Changing Notions about Teaching and Studying Writing

	Early Research	Recent Work on Process	Recent Work on Context
How Do We Define Writing?	As a finished product	As a complex cognitive process	As a cognitive process embedded in a social context
Who Among Our Students Can Write?	Those who have the "right stuff"	Those who have a robust writing process	Those who have gained entry to a discourse community
What Is Writing Research?	Error counts and quality assessments	Process descriptions	Analyses of the interactions among processes and contexts
What Is Writing Instruction?	Marking and responding to finished products	Providing practice in the process of writing	Creating discourse communities with authentic tasks and social interaction

that teachers and researchers were long concerned only with written products that could be graded, corrected, or analyzed: book reports, letters, themes, and research papers. Teachers marked and graded papers, but they did not help students produce them. Researchers tallied textual features and calculated their frequency but did not concern themselves with how words got to the page. Writing was a skill that one either possessed or did not, a process students experienced through native genius or discovered through trial and error. Perhaps because the final written form of an essay is coherent and structured, it seemed reasonable to assume that writing proceeds that way, too: correct-and-measured sentence by correct-and-measured sentence, one rolling effortlessly after the other. Such an understanding of writing would obviate any attention to process or to students whose written products failed to measure up.

That writing does not always proceed in measured and orderly steps, and that the process is one that can be analyzed and taught, have been the first great discoveries of writing research in this century. Like researchers in other disciplines who also study mental processes, writing specialists found a way to define with clarity and character the invisible mental acts that comprise producing written language. By asking writers to think aloud as they wrote, saying whatever thoughts came to them in the midst of composing, researchers learned that writing consists of several main processes—planning, transcribing text, and reviewing. They also learned that these processes don't occur in a particular order; rather, they take place recursively, with the writer stopping to plan in the midst of transcribing a paragraph or beginning to revise before she even has a word on the page. To "listen" to a writer compose is to appreciate complexity: planning what to say next, choosing the precise word, thinking of a better way to phrase a sentence, remembering another example to include, correcting a misspelled word. These are all operations that can occur in the space of seconds. To appreciate such complexity is to understand how an inexperienced writer can get derailed, for part of learning to compose is learning to balance the many things that writing asks a person to do at once, and learning to put off some concerns until later.

The research on composing has taught us to think of writing as a "problem-solving" process, to view it as a set of conscious cognitive and linguistic behaviors like planning, organizing, structuring, and revising. We've learned as well that experienced and inexperienced writers solve the problems posed by writing quite differently. Researchers like Flower and Hayes (1980) have shown us that better writers develop flexible goals to guide their writing processes. These goals are "rich enough," they say, "to work from and argue about, but cheap enough to throw away" (p. 43). Poorer writers tend to spend little time planning, rushing to commit words to the page, and to hold tight to their initial formulations of a problem. Expert writers also differ from novices in how they approach the task of revision, spending much more time on improving the meaning of their texts. Novices, on the other hand, tend to make cosmetic changes that may improve wording or correctness but do little to reshape a discourse. In fact, a great deal of research has shown that inexperienced writers focus so much attention on trying to correct errors in spelling and grammar that they don't do the rest of writing any justice.

Perl (1979), for example, demonstrated how a premature concern for editing, or correcting errors, can create misery for unskilled writers. One of these writers was a young man named Tony, born and raised in the Bronx. Of Puerto Rican ancestry, he spoke Spanish but considered English his first language. Tony dropped out of high school in the 11th grade and returned three years later for an equivalency diploma. At the time of Perl's study, Tony was a student at Hostos Community College of the City University of New York. Perl asked Tony to think aloud as he wrote, then analyzed the behaviors that made up his writing process. Here is one of the essays he wrote for Perl on a topic from an introductory social science course on society and culture.

> *All men can't be consider equal in a America base on financial situation. Because their are men born in rich families that will never have to worry about any financial difficulties. And then theyre are another type of Americans that is born to a poor family and alway my have some kind of fina—difficulty. Espeicaly nowadays in New York city With the bugdit Crisis and all. If he is able To get a job. But are now he lose the job just as easy as he got it. So when he loses his job he'll have to try to get some fina—assistance. Then he'll probley have even more fin—difficulty. So right here you can't see that In Ameri, all men are not create equal in the fin—sense.*

Readers unaccustomed to working with student writers are likely to despair at the many errors in syntax, grammar, and spelling in Tony's paper and to question his energy and commitment to schooling. But Perl found that editing—paying attention to error—was actually a big part of students' composing processes. In fact, Tony never wrote more than two sentences before he paused to examine them for errors in spelling, punctuation, or word choice. Of 234 changes that he made in the essays he wrote for Perl, 210 of them had to do with attempted error corrections. Also startling was the fact that Tony read his writing aloud correctly, although he did not notice the discrepancies between his oral version and the words on the page. Tony "read in" missing words and word endings; he pronounced abbreviations and misspellings as if they were correctly written. In short, he read the desired word rather than the one on the page.

Perl believed that editing often intrudes so much that it blocks writing and thinking. Similarly, other researchers (see Rose 1984, for example) have found that inexperienced writers have developed rigid rules and dysfunctional strategies that serve them poorly. "You shouldn't ever have a passive verb," these writers will report, or they will insist, "My first sentence must be perfect before I can go on." It follows that inexperienced writers will likely need some help with ordering and structuring the writing process, in learning, for example, to give full play to generating text, to putting words on the page, and to delaying a concern for error until later. And it is likely that they will need some help in learning how to edit—not the help provided by traditional worksheets on grammar points, but help in developing procedures for seeing mistakes and deciding how to correct them.

The last 15 years of writing research have moved us some distance, then, from thinking of writing just as a product, of students as having or not having the right stuff, of research as the analysis of textual features, and of pedagogy as the marking or correcting of products. We've learned to think of writing as a complex cognitive process; of students as possessing immature, incomplete, or perhaps flawed representations of that process; of research as the description of process; and of pedagogy as providing instruction on the process and occasions to experience it. I can hardly overstate the significance of this work; it has restructured the thinking of teachers and researchers in fundamental ways.

But we've heard just half of the tale. There has been another great revolution in our thinking about writing in recent years, and it has come from learning to view writing as a process that is embedded in a context. Again, it may seem only common sense to acknowledge that writing takes place in a setting. What is being claimed, however, is much more radical than first reflection is likely to reveal. To say that writing is embedded in a context is to acknowledge that what counts as writing, or as any skill or any knowledge, is socially constructed. It depends for its meaning and its practice upon social institutions and conditions. According to this view, writing doesn't stand apart from people and communities: There is no single writing process waiting for discovery and use. Rather, writing as a kind of literacy "is permanently and deeply ideological, and teaching it means inculcating and reproducing a specific set of values and evaluations" (Salvatori and Hull in press). Our new understanding of writing is found outside individuals and individual cognitive acts, situated within a broader context of institution, community, and society. And this new understanding carries with it different notions of how writing is acquired and by whom and, as the following studies demonstrate, different notions of how to carry out research on literacy acquisition.

A piece of scholarship that has contributed greatly to our view of writing as socially embedded took place far from American classrooms. Scribner and Cole (1981a, 1981b) studied literacy acquisition among the Vai, a West African population of about 1,200. Many Vai are illiterate, but some are literate in English or Arabic, and some also know an indigenous form of writing invented by the Vai almost a century and a half ago. Still in active use, this script is transmitted outside of formal schools. The fact that the Vai acquire literacy without formal schooling—a condition that is not common in our own society—allowed Scribner and Cole a clear avenue to investigate the relationship between literacy and thinking without the confounding effects of schooling. In doing so, they also studied how literacy is acquired and practiced among the Vai.

Scribner and Cole found that the Vai used English as the official script in national political and economic institutions, Arabic in religious practice and training, and the Vai script for personal and local communication and record keeping (letter writing, list making, journal keeping, or brief histories). In terms of the intellectual consequences of being literate, Scribner and Cole demonstrated that literacy is associated with improved performance on certain cognitive tasks, but not with improvement in overall mental abilities. For example, learning the Koran improves certain kinds of memory skills, but not memory in general. Scribner and Cole came to believe, then, that "literacy is not simply knowing how to read and write a particular script but applying this knowledge for specific purposes in specific contexts of use. The nature of these practices . . . will determine the kinds of skills ('consequences') associated with literacy" (1981a, p. 236).

Closer to home, Shirley Brice Heath (1983) studied a plurality of literacies among people in three communities in the Carolina Piedmonts—the inhabitants of Trackton, Roadville, and "the Town." She documented the ways adults in Trackton and Roadville (black and white working-class communities, respectively) differed in language-using practices from the townspeople (mostly middle class whites). Although all three communities were literate—that is, their uses of reading and writing were "functional" within their own communities—there were mismatches between language practices at home and in school for the Trackton and Roadville youth. The language use that these children had acquired in their home communities did not, it turns out, prepare them for the kinds of reading and writing tasks that were the sine qua non of school.

Studies like these, and the theories of literacy acquisition that inform them, have inspired a great deal of revisionist thinking in terms of how we define writing and how we envision practice. For example, we are beginning to think of writing not as a single concept or process but as a plurality. We expect what will be valued as an expert writing process and product to vary, depending on what function that writing will serve, for which people, at which time. We are learning to question, therefore, any model of writing that is monolithic—that, for example, holds up one kind of text or prefers one kind of process as prototypical and ideal. We are beginning, as well, to acknowledge the importance of social interaction in the acquisition of literacy skills. People learn to write, as Langer (1987) explains, "in social settings where reading and writing and talk about language have particular uses for the people involved" and "when learners see models of literate behavior as other people engage in literacy activities, and when they talk and ask questions about what is happening, why, and how" (p. 11). And we are beginning to conceptualize the difficulty of learning to write as enculturation into a community or a discipline. Writing is a complex cognitive skill, to be sure, but the nature of the problem that a writer must solve takes on awesome new dimensions when we view it in its social context. "Every time a student sits down to write for us," explains Bartholomae (1985), speaking of undergraduate education, "he has to invent the university for the occasion." That is, he must "learn to speak our language, . . . to try on the peculiar ways of knowing, selecting, evaluating, reporting, concluding, and arguing that define the discourse of our community" (p. 134).

One of the problems facing teachers and researchers is learning to recognize and honor a student's attempts to take on the language of a new discourse community. In a study of underpreparation in literacy skills, Hull and Rose (in press) document such an attempt by a 19-year-old woman in a basic reading and writing class. One of the writing tasks that Tanya faced was to summarize a simple case study written by a nurse, "Handling the Difficult Patient." This case study was chosen for its appeal to Tanya, who wanted to become a nurse's aide or a licensed vocational nurse. In the case study, the author gives a first-person account of her experiences with a recalcitrant patient. The summary that Tanya wrote is reprinted below. It seems incoherent until we understand it as an inexperienced writer's attempt to enter a discourse community by taking on a new language.

> The Handling About
> difficult patient
> this something telling about
> a nurse ~~to~~ who won't to
> help a patience.
> She was a special night nurse,
> this man had a stroke and

was ~~paral~~ paralsis on his
left side. She Was really
doing a lot for the patience
She Introduced myself
she asked him How was
he feeling. remark was,
XXX, can't you see 'Im in
pain?" he telling the nurse
he was in so much pain.
he really didn't won't
to answer her. Before
she was ready to give
him his I.V. Are Anything
XXX "you're killing me,
you XXX."
Oh this going to Be a great
Day I said to myself
just thinking alone.
I have pride in What
I Do I am going to get
pad no matter what I am
still ~~am~~ going to collect
my money no matter
what happen I do Believe
and I no that In ~~my~~ mind.
My thoughts were similar
but deep down.
What was the approach?
A Registry nurse
was so descriptive.
impossible for me to
find a replacement.
My second and thirddays
she decided she ~~won~~ wouldn't
Abuse any longer and
~~Aso~~ also left the case
felt Abandoned was an
understatement; even
this doctor In this case
she Really liked what she
was doing But was getting
treated Right Respect.

She had chance of getting
A another job But+Don't
she wanted to But then again
She wanted to.

Hull and Rose account for some of the problems in this summary by explaining Tanya's inaccurate plagiarism rule: "change a few words so as not to copy." Another idiosyncratic rule that seemed to govern her construction of the summary had to do with selection. Tanya reported that she altered sentences from the original not only to avoid plagiarism, but because "the parts about the nurse are something about me . . . you see, 'I have pride,' you see, I can read that for me." Although she chose some details to include in her summary because they were important to the original text, she chose others because they were personally rather than textually relevant. Hull and Rose point out Tanya's repeated assertions that she will be able to learn and succeed ("I know I'm capable of doing anything in this whole world really")—assertions made in the face of great odds. And they argue that such goals and dreams allowed her to identify with the nurse in the case study and also oriented, to a disproportionate extent, how she constructed this particular literacy task. Although Hull and Rose acknowledge the serious flaws in Tanya's essay, they also argue that this piece of writing illustrates the presence of "something profoundly literate": the appropriation of a language to establish membership in a group. Tanya tries on the nurse's written language and, with it, the nurse's self. A productive pedagogy for this student, then, would be one that first encourages such imitation, honoring the important connection between Tanya's text and her goals for herself, and helps her learn the conventions for producing a discourse like the nurse's.

Thus, literacy researchers are learning of late to broaden their notions of writing as a complex cognitive process, of students as possessing immature or incomplete or perhaps flawed representations of that process, of research as the description of process, and of pedagogy as providing instruction on the process as well as occasions to experience it. We are coming to weigh the implications of the social construction of literacy, and to think of writing as a process that is by its nature embedded in a context. We are coming to think of writing instruction as providing opportunities for students to learn culturally valued skills. We are coming to think of students not as deficient in the right stuff, not just as possessing the wrong writing process or an underdeveloped one, but as initiates to new discourse communities. We are coming to think of research not only as describing and understanding a process, but as describing and understanding the interplay of processes with contexts. These changing notions about teaching and studying writing are summarized in Figure 6.1. They are further illustrated in the next section, which offers a detailed example of writing instruction and a collaborative research effort.

Basic English in the Deep South

The class is 9th grade English in a Deep South high school. There are 18 students: 14 black, 4 white. Fifteen of them are labelled mentally inferior since they scored between 65 and 85 on the Stanford-Binet. Before this school year, all but three of these students had participated in a special education program that focused on remedial work in reading, math, and the mechanics of language use. Only three students had previously read an entire book or written any prose longer than three to five sentences. Their high school offers two academic tracks: "general" for those with prospects of college or technical school and "basic" for those previously in special education or who scored below grade 5 in reading and language skills. This class is basic English.

The teacher is Amanda Branscombe. She starts the year by telling students, "You all have A's. Now let's settle down and learn" (Heath and Branscombe 1985, p. 5). She has a mandate from the state to have her students work through certain curricular materials involving matching, fill-in-the-blanks, and spelling exercises. But throughout the year, Branscombe will not teach grammar or spelling in the traditional sense of providing direct group instruction on rules or in marking the errors in students' written work. Rather, she will treat all her students as capable readers and writers, provide them many occasions for literacy activities, and talk about cognitive and social processes—such as what students think they are gaining from writing, how they connect it to their lives outside the classroom, and what and why they are writing. She will continually stress that what counts in her class is whether students communicate in writing in ways that make sense to their audiences and whether they show that they have something to say. Instruction on errors will occur in the context of students' particular problems in their own papers.

This year Branscombe has organized what she wants students to learn around the literacy practice of letter writing. In September, she paired members of her 9th grade basic English class with members of her 11th and 12th grade general English class on the basis of the interests they described in introductory essays. Because the school was large and the two-track system served to segregate students, these letter-writing partners had little chance of meeting. The upperclassmen were supposed to write to the 9th graders once a week with the intent of helping them improve their writing. Branscombe gave the students no specific instructions on how to format their letters, nor did she direct them to rework their writings to improve content or mechanics. But she had great expectations that over the semester the 9th graders would:

1. see the upperclassmen's writings as models of acceptable personal letters;

2. become engaged with a distant audience known only through written communication—and accept that "somebody cared" about their writing other than the teacher;

3. recognize writing as communication: writing in school did not have to simply be a way of completing an assignment; it could also be an occasion for practicing widely used communication skills needed to reach varied and distant audiences;

4. participate willingly—and with a notion of a responsibility to "make sense"—in types of writing that had different functions; and

5. move beyond initial response in writing to engagement with ideas: to be willing to explain and question their own ideas in writing to assist their audiences in understanding their meaning (Heath and Branscombe 1985, p. 10).

Ninth grader Cassandra was paired with two 11th grade girls, J. and A. Here is the introduction she wrote to them.

> My name is Cassandra. There's not much too say, except that I have a lot of ups and down's. I love to play sports, especially volley ball. I hope who ever reads this letter finds the personal Cassandra. We'll are you going to the game Friday. Well as for me, I'm not sure. My boyfriend want's me to go with him, but with things like they they are now, I'm not sure what my next move is. Oh and did you [know] who my boy friend is. (J O). And if you're not w rying about [it] then excuse me. I would appreciate if you wouldn't inform me about this letter. But it's o.k. because most of this stuff is just in the head. Well so-long kid. And have a nice day.
>
> P.S.—Hope you don't mind me saying kid.

J. and A. responded by pointing out the parts of the letter they did not understand—such as, "I hope whoever reads this letter finds the personal Cassandra." Cassandra's answer was a letter in which she opened with a salutation and responded to each item raised by J. and A., beginning with a restatement of the point they wanted her to clarify: "We'll [Well] for the up's and down's." She also reminded her pen pals that she had things to ask them, too: "We'll [Well] I'm answering your letter back, and I have question's that I want to explain and maybe ask some."

The letter exchange continued with the older students asking questions and Cassandra dutifully answering them, albeit with some omissions and mysterious interpolations. A turning point of sorts was reached with the fourth letter from J. and a complaint about Cassandra's failure to make sense.

> Hello. I just discovered you haven't written me a letter this week. I guess I'll have to struggle through this without your letter of response or A. shes not here today. Although your letters never were much to begin with. I'm probably better off talking to myself because your always so *damn* confusing. Maybe if you re-read or proof read your letters your might catch some of the strange things youve been saying. I think you probably try to say things with good intentions but it just comes out awkward with no meaning. Getting off the subject and forgetting the point your trying [to] make can happen to anyone every now and then but your constantly doing this. I have to give you credit for your handwritting and spelling, that's not the problem. Next letter try to make all of your sentences clear. Don't *assume* I know what your talking about. *Explain* everything.
>
> I'm not trying to "get down on you" or "get on your case." But, before we become friends I have to know what your saying or asking to respond (Heath and Branscombe 1985, p. 12).

Here is part of Cassandra's response, a letter with no salutation but with her full signature and her "philosophy of communication."

> But you and I are to different person's you know. And I've tried to explain myself as much as I could, but somehow you just don't get the message. What do you mean about my letters being confusing. I explain the things I write about the best I know how. Maybe they are confusing to you but I understand what I write. I don't think that it's confusing to you. I think that you just felt like getting me told a little. And

> as for A. I know that she wasn't here, but I would like to know [does] she feel the same as you. We're still friends in my book. and if it's something you want to know I'll try and make myself clear. I hope that this is not so damn confusing. And if it is the Hell with the stuff (Heath and Branscombe 1985, p. 12).

The letters the girls subsequently wrote were longer and covered more subjects. Cassandra began to anticipate the parts of her letters that would prove troublesome and to ask her correspondents to let her know if they did not understand her. As the Thanksgiving and Christmas seasons approached, Cassandra began to write more about the loneliness she would feel without her mother, who had died the first week of school. J. confided that she had lost her own mother through divorce but that she had become a stronger person in the process. Cassandra's last letters of the year told her pen pals that they were the only friends she had had all year.

During the second semester, Branscombe arranged for her 9th graders to have a more distant audience and other purposes for writing. Shirley Brice Heath, an anthropologist living in California, began to correspond with the class on how they might become her "associates" in her work as an ethnographer of communication in different parts of the world. With Heath's direction, provided through her letters, the students began taking field notes on how language functioned in their own communities. The idea was that such activities would make them linguistically aware speakers and writers, give them practice in recording information, and give them a chance to be informed critics of their classmates' reports and interpretations of data. Students not only wrote letters to Heath, they also wrote field notes, field-site descriptions, autobiographical essays, personal essays, and explanatory essays analyzing their field notes.

While their letters to upperclassmen had focused on topics of shared context that required little detailed description (like school sports and dances), they had rarely referred to events in the distant past or to people and activities not directly involved in their lives. Thus, Branscombe saw the correspondence with Heath as an occasion for students to practice different kinds of communication: "(a) detailed explanations and assessments of past events, (b) descriptions of current scenes, actions, and people, and (c) arguments defending their course of action, point of view, or interpretation" (Heath and Branscombe 1985, p. 20). The correspondence was also a chance for the students to become a "community of ethnographers" (Heath and

Branscombe 1985, p. 7) who would jointly construct and transmit knowledge and who would experience the benefits of this cooperation: being a party to work that others could question, interpret, react to, and develop.

Heath wrote long, word-processed letters to the class as a group, not to individual students. She wrote about being an anthropologist, about the places her work took her, and about the students' letters and tapes of their interviews with people in their community.

> Since you will not be writing letters [to your pals] this semester, I had hoped to ask you to help collect fieldnotes for me. Fieldnotes are the records anthropologists make of what happens in life around them in the place they are living. I have lived and written fieldnotes in many parts of the world. Some of you may want to look at the map and see where these places are, since I had not heard of many of these places until I was much older than you are. I worked first in Guatemala and Mexico, living among Indian groups there and studying their children at home and at school. Then I went to Japan and went to the most northern island—Hokkaido—where I studied the rural people and their ways of coping with modern life—cars, televisions, roads, and tape recorders . . . (Branscombe 1987, p. 213).

Branscombe made copies of Heath's letters for each student, and they read the letters in groups, "negotiating meaning and interpretations as a community" (Heath and Branscombe 1985, p. 17).

The students wrote personal letters to Heath, like this one from Cassandra.

> Shirley I've gotten to know you more than I thought I did. You're very sweet. I think that you would go out of your way to help us as much as possible, and anyone else. [The following questions are with reference to a tote bag that Shirley sent to Cassandra when she returned from her trip to Brazil.] Shirley I would like to ask you a question or 2. What does Chemin de Fer, means? Does it mean that that the name of the company that manufacted it? [The tote bag] Or it's the name of a building (Branscombe 1987, p. 213).

They also wrote to ask questions about the process of ethnography. For example, "How much detail do I have to give on the layout of the filling station where I'm describing the language the mechanics use?" "What's different about recording information and interp. eting it?"

In addition to personal letters, the students expanded their writings to include field notes, interviews, and observations. Here, for example, are excerpts from the observations one student made about the kind of reading he observed.

> Friday After School
>
> My neaighbor was reading the O-A News. (A local newspaper) My aunt look at the mail when she got home and read the HBO book to see what was coming on TV. My uncle looked in the phonebook for a number.
>
> Saturday
>
> I read a record cover and looked at a magazine. I read a candy lable (Sneaker). I also read the names on the T.V. screen when a movie came on. I read a Kodak film box . . . (Branscombe 1987, p. 215).

Branscombe and Heath directed students to write their fieldnotes quickly, putting on paper as much as they could. Revision came later when they were writing essays in which they interpreted their notes. On occasion, Branscombe and Heath pointed out errors in grammar or style in the context of something students were trying to communicate. For example, during a visit Heath made to the school in May, she explained to Cassandra, in a long conversation about her fieldwork, that she would need to use apostrophes correctly and to distinguish the spelling of *to*, *two*, and *too* and *no* and *know*. Heath then explained these errors to Cassandra, noting when and why apostrophes are used to show omission and possession. "'Why hadn't anyone ever told me about apostrophes like this?'" Cassandra wanted to know (Heath and Branscombe 1985, p. 25). Subsequently, she made no errors on these grammar points in her letters to Heath.

As the semester progressed, Heath began to be less personal in the style of her letters, omitting vocatives and first and second person. She provided long, depersonalized explanations, and did not explain why materials or tasks would be important to the students. Again, the intent was to move students from here-and-now writing to composition tasks for distant audiences on depersonalized topics. This shift was not easy for everyone. Eugene tried to persuade Heath to write individual letters to each student.

> I may be wrong but I don't think so. You see Miss Branscombe is having all of us write to you. But in your last letter you only said that you would only write to some of us and I

> think that you should write to all of us. Because all of us are writing to you. If you don't want to write to me than I want [won't] write to you or tak any field notes. I think you will agree with me if you don't then put your self in our shoes and if you still dont then let me know (Heath and Branscombe 1985, p. 24).

Gradually, students came to understand that Heath expected their written products—their field notes and interpretations of data—to compare favorably to the work of other ethnographers. And gradually they came to understand the lengthiness of the writing process, realizing that a final product was far in the future and that it would be preceded by many discussions and revisions.

After the semester was over, Heath and Branscombe and the students examined the letters written over the year to see if the students had reached the goals their teacher had set. These analyses showed that Cassandra had changed from simply answering queries to initiating topics and sustaining commentary on them. Accompanying these discourse changes were changes in textual features like markers of cohesion. Whereas the students' first letters were characterized by additive and adversative connectives like *and* and *but*, their later ones made use of causal and temporal connectives like *so*, *that*, and *when*. Students wrote longer letters as time went on, and they read more as well: news items, magazines, stories, and novels. They had become, say Heath and Branscombe, communicators adept at using written language for different audiences and purposes.

But there are other ways to measure success. Cassandra had started the school year refusing to sit at a desk, choosing instead to sit on top of a table in the back of the classroom, her back facing the class. She sat cross-legged, often sucking her thumb. When she later moved to a seat at a desk, she was hostile to students who disturbed her with their comments or noise. As the year progressed, she joined the community of the classroom. She wrote more than anyone in class, and she assumed a leadership role, pressing others to work hard. As one of her classmates said, " 'Cassandra is our number one leader in the group because of her knowledge and skill' " (Heath and Branscombe 1985, p. 9). At the end of the school year, she chose to continue the research project with Heath. She eventually transferred to another high school, where she was placed in an honors English class.

Three Maxims for Writing Instruction

Amanda Branscombe's class is one illustration of fine writing practice. It is also an illustration of how times can change in terms of who we believe can write and how we go about studying that process. In the discussion below, I'll use Branscombe's class, along with other classroom accounts, as touchstones for understanding and testing some maxims for writing instruction that I have derived from current literacy theory and research.

1. Learning to write requires tasks that are "authentic."

The revolution in writing instruction started with a simple realization: To learn to write, students must partake of the process. For many years, when we claimed to offer writing instruction and writing practice as a part of English class, we actually offered something else—instruction and practice in grammar, most often, or in diagramming sentences, reading literature, or speaking correctly. For Amanda Branscombe's students, writing had previously meant worksheets on spelling and grammar. Time for the process of composing was not so common. Teachers and researchers have come to realize that there simply must be time in the classroom when students write, not perform some other activity that stands for writing, and that students need to have writing represented as a process. For example, students need to understand that most people don't and can't ordinarily take a one-shot approach to an important writing task; rather, they engage in the task over time, often with the help of several readers who respond to the style, substance, and inventiveness of the composition. Branscombe's students, you will recall, worked over the interpretations they gave their field notes for weeks, negotiating together the meaning of Heath's responses to their letters.

In one sense, then, if a writing task is to be "authentic," it must pay homage to writing as a process. But authenticity, as I am using it here, means something more. We must also find a way to represent writing not as a process that is an end in itself, but as an activity that allows a writer to accomplish some larger, authentic communicative purpose. Branscombe's students used writing to communicate to someone else information they had collected and interpreted, and this task they understood to be "real" or authentic. They were engaged as associate researchers with Heath in a project they learned to value. Brown, Collins, and Duguid (1989) have recently written about education as enculturation, a process by which learners come to view and to use knowledge from the perspective of members of a discipline, community, or culture. Children learn to do math, according to this view, by learning what mathematicians view as a problem, what they count as a solution, and what forms of proof they allow, and they do so by engaging in activities that the subculture of mathematics views as "authentic." Brown and colleagues argue that many of children's school activities can in no manner be termed authentic because they "would not make sense [to] or be endorsed by the cultures to which they are attributed" (p. 34). I think something similar has been true of writing instruction. So many of the things children do in the name of writing are school-bound, having no counterpart, or one of a radically different kind, in the world beyond the classroom.

Witte (1988) has shown that writing in particular workplace contexts is different from writing in particular school contexts by being socially and cognitively more complex. For example, he saw writers in the workplace, unlike student writers, using multiple literacies and symbol systems; being a part of more and more various collaborations during the writing process; having to address multiple audiences with single texts; needing to rely upon information that audiences wouldn't be familiar with; dealing with constraints that come from knowing a particular text will have a great deal of influence. I don't mean to suggest that a writing task, if it is to count as authentic, must take place in the outside world of book publishing and research or some other "real" activity or that young and inexperienced writers should be expected to manage on their own the same writing tasks as adults and experienced writers. Writing tasks will be authentic in the sense that I'm after when they give writers reasons for communicating—reasons that a classroom community experiences as legitimate. This can take many forms. And as discussed below, novice writers will certainly need help in carrying out complex writing tasks.

2. Writers can acquire new knowledge and skills through "scaffolding."

In a fundamental way, each time we ask a novice to attempt an authentic writing task, we are asking him to do something he is not ready for and cannot do on his own except in a flawed, incomplete fashion. Amanda Branscombe's students were not letter writers or ethnographers of communication. David Bartholomae's undergraduates could not invent the university. If, as argued above, giving students pseudo-tasks amounts to non-writing, then we must make it possible for students to stretch beyond their current competence to engage in authentic tasks. This is all the more important for students like Tony and others traditionally placed in remedial programs, for if we don't find a way to help them do what is currently beyond their reach, we will permanently relegate them to activities that are substitutes for genuine literacy tasks.

Cole and Griffin (1986) report how they adopted from Brown, Palincsar, and Armbruster (1982) an instructional technique called "reciprocal questioning" for use with elementary school students who were poor readers. Realizing that these students had impoverished notions of what reading consisted of—something like "read the individual words so that they sound right"—Cole and colleagues set about providing the scaffolding by which students could experience reading as expert adults do, "as a process of interpreting the world beyond the information given at the moment" (p. 126). They developed a "script for reading" with four acts: goal talk, paragraph reading, test, and critique. Goal talk was conversation about purposes: Why do people read? What does it have to do with the world of work? Why do adults ask questions when they read? Paragraph reading was scripted talk about individual paragraphs. Having read a paragraph, students asked themselves and each other questions on cards previously shuffled and distributed, questions like: "ask about words that are hard to say" and "whose meanings are hard to figure out"; "ask about the main idea"; "ask about what is going to happen next" (Cole and Griffin 1986, p. 123). The children carried out these activities in collaboration with an adult or undergraduate; thus, they saw the activities they were asked to engage in modeled by more knowledgeable others, and they gradually internalized this model. "The crucial feature in these activity settings," say Cole and Griffin," "is that the adults, coordinated around the reading script and a shared knowledge of what reading is, create a medium in which individual children can participate at the outer reaches of their ability" (p. 124).

The vehicle of scaffolding in this instance, and in many others as well, is social interaction. There was a time when administrators could presume to judge a teacher's competence and her students' good will by orderliness and quiet in the writing class; that time is no more. Often the classroom is filled with student talk, and often it is decentralized, with students working in pairs or small groups and the teacher sitting among them or walking from one group to another. According to Vygotskian ideas about the social origin of learning, children become literate—they acquire the requisite and valued knowledge and skills—in an interactive social setting. In such a setting they can have help from adult models and their peers as they gradually internalize the structure and uses of particular literacy activities.

Applebee (1984, pp. 180-181) offers the following questions as guides to analyzing the appropriateness of instructional scaffolding, whether it is conveyed through textbooks and worksheets or classroom talk.

1. Does the task permit students to develop their own meanings rather than simply following the dictates of the teacher or text? Do they have room to take ownership for what they are doing?

2. Is the task sufficiently difficult to permit new learning to occur, but not so difficult as to preclude new learning?

3. Is the instructional support structured in a manner that models appropriate approaches to the task and leads to a natural sequence of thought and language?

4. Is the teacher's role collaborative rather than evaluative?

5. Is the external scaffolding removed as the student internalizes the patterns and approaches needed?

Applebee reports that there is not much evidence, in the classrooms he and his colleagues have observed, of appropriate instructional scaffolding. Classrooms remain teacher-centered, emphasizing the teacher's goals rather than the students' purposes. Tasks are either very structured—like fill-in-the-blanks exercises—or very ill-defined—like answering an essay question. The teacher's role is usually to read and correct students' writing.

On the other hand, Amanda Branscombe's classroom—a classroom for supposedly "basic" students—shows evidence of appropriate instructional scaffolding. Students "owned" the tasks assigned by Branscombe and Heath even to the extent of continuing them after the semester ended. The tasks were challenging, to be sure: be an associate ethnographer, collect field notes, and analyze and interpret them. Yet students were able to carry them out with appropriate structuring: Branscombe had students first write letters about the here and now to their peers and then to Heath, who gradually changed her discourse from personal to impersonal, from narrative to exposition. And Branscombe was a collaborator, not an evaluator: "You all have A's," she announced early on. "Now let's settle down and learn."

3. A writer's performance has a history and a logic.

In a recent study involving college writers, Flower (1987) examined the task of "reading in order to write." Students were asked to read selected passages and then to write a brief paper in which they interpreted and synthesized those readings. One interesting finding from this study was that students represented the task to themselves in many different ways. One student assumed, for example, that the assignment called for a "gist and list" strategy: read the texts, find the key words, then summarize. Another student saw the assignment as an invitation to talk about what she already knew, using the passages as jumping off places for her own ideas. Others vacillated between these two approaches, summarizing and then commenting on the summary. And there were other approaches as well. This study is a welcome reminder that students represent a wonderful diversity: They come to our classrooms with behaviors and ideas that they acquired elsewhere—in other classrooms, from other teachers, at home, and from family and friends. It is also a cautionary tale about the dangers of a common unspoken assumption—that students share our language, our procedures, our values, and if they don't, they are somehow aberrant or deficient.

Our abilities to appreciate diversity and to understand its impact on learning have improved over the last 15 years, due largely to the efforts of sociolinguists and anthropologists. There has been a burgeoning of studies in these fields that juxtapose the norms in classroom life with the language skills, knowledge, and assumptions about learning that children acquire in their homes and communities. This juxtaposition has often revealed differences that matter a great deal in learning. For example, in a study of Hawaiian children and their reading instruction, Au and Mason (1981) showed how important it is for the conversational patterns in reading groups to be culturally congruent with conversational patterns in the community. Among working class Hawaiians, it is customary to tell and discuss stories in small groups with the members speaking simultaneously. Such overlapping isn't viewed as impolite but is seen as an indication of engagement and interest. However, when children apply the same conversational rules to reading groups, where teachers are accustomed to calling on children and having each speak in turn, teachers who don't know about their custom consider it disruptive and spend a disproportionate amount of time trying to call the class to order. In contrast, Au and Mason found that when teachers allowed reading group talk to be carried out in a manner more culturally congruent for the Hawaiian children, rather than trying to impose the customary pattern of one speaker at a time, the children spoke more coherently and learned more.

It is inestimably important for writing teachers to assume that any learner's performance has a history and a logic; to assume that, even though a piece of writing is flawed, the student isn't somehow cognitively or linguistically deficient; to assume that the right set of keys will unlock a piece of writing for a reader and make it coherent and understandable. Something like these assumptions allowed Amanda Branscombe to believe her basic English students could be ethnographers and could correspond with a famous researcher and with 11th graders on the "general" track. Such assumptions informed the research of Hull and Rose and their case study of Tanya and her seemingly incoherent composition. They were ground rules for Perl as she examined Tony's truncated, incorrect texts and his complex composing process and came to understand the great store he placed in editing. It is inestimably important to assume a learner's performance has a history and a logic not only because this assumption gives us a way to understand and investigate students' difficulties with writing, but because the logic and history may identify what is appropriate (and inappropriate) instruction. What is effective "scaffolding" for some students—collaborative learning techniques, for example—may be culturally incongruent for others (Langer 1988).

Conclusion

Historically, literacy has been our talisman, variously expected to boost employment, ensure intellectual growth, and promote civility. Scholars today are apt to question the grand benefits traditionally assumed to be certain consequences of being able to read and write (e.g., Graff 1979, Scribner and Cole 1981a, 1981b). They point out, for example, that it will take a lot more than rudimentary reading skills to improve a person's economic lot, or that learning to write might promote specific kinds of thinking skills, but not improve mental abilities in general. Such revisionist thinking has been possible in part because scholars have examined the acquisition of literacy skills in the larger contexts of their nature and functions in community and society. That is, they have looked at reading and writing not by examining a few people in isolation working on contrived tasks, but by examining actual situations of schooling and community-based literacy use.

Something similar has happened to research aimed particularly at the teaching and learning of writing. After some years of examining the texts that writers produce or their individual writing processes, researchers have started to study texts and processes through the lens of context. Central to this shift is the belief that writing is embedded within society and depends for its meaning and its practice upon social institutions and conditions. Viewing writing in this way throws in bas-relief the actual roles that writing can play in people's lives as well as the conditions under which it is acquired. The result of such investigations has not been a devaluation of writing, but an appreciation of its social basis, in particular, the varied ways social context affects knowledge acquisition and orients cognition. Understanding writing, then, has increasingly come to mean an understanding that is at once cognitive and social. Or to borrow Erickson's (1982) metaphor, we are learning in writing research "how to focus closely on the trees without forgetting that the forest is there too" (p. 153).

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7

Teaching Science for Understanding

James A. Minstrell

Early in my experience as a high school science teacher, I became concerned about my ineffectiveness at teaching students to transfer their understanding. I don't mean that I was a bad teacher. My students tested well, and my administrators gave me glowing evaluations, but I was amazed at the relatively little effect I had on my students' understanding of the ideas of physics.

In the early 1970s, I, like others, thought the difficulty might be my students' lack of ability with formal operational reasoning. However, in my investigations of students' operational reasoning capacity, I found that the results of reasoning tests depended on students' conceptual knowledge. For example, consider a task involving two equal-sized balls of clay. After establishing that the two balls weigh the same, one of them is flattened into the shape of a pancake. Students are again asked to compare the weights. The task tests students' understanding of the operation of conservation, in this case

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conservation of weight. Many students "fail" the task not because they can't do conservation reasoning, but because their concept of weight or gravity involves air pressure, and a flattened ball of clay has more upper surface on which "air presses down." This represents a conceptual error rather than an operational reasoning error. Students are bringing to the situation content ideas that greatly affect their performance on questions that are supposed to test their operational reasoning. Even on problems that require the same abstract reasoning on similar quantitative data, the specific content of the situation affects the reasoning strategies students use.

The growing research on students' conceptions in the late 1970s helped me become more effective at teaching for the understanding of ideas, especially on problems requiring transfer of conceptual understanding to novel situations. In this chapter I describe how my experience in the classroom and the research on cognitive processes and related areas now guide my teaching. My teaching is more informed, and I have specific conceptual goals, based on recent information about the cognitive nature of the learner and the nature of the learning process.

The first section includes annotated descriptions of a lesson about force, a central concept in Newtonian physics and one of the topics in physics learning that has been heavily studied by cognitively oriented researchers. The next section gives further examples from two additional lessons that illustrate the care needed in designing and implementing instruction aimed at fostering conceptual restructuring in the science classroom. Finally, I discuss and summarize the major instructional principles to be drawn from cognitive research on science learning. Although all the examples in this chapter are from physics, my colleagues assure me that the principles apply across the sciences and beyond.

An Introductory Lesson on Force

Students come to the classroom with initial conceptions organized by their experiences. While it is probably true that each individual has a unique set of past experiences, there is remarkable consistency among the naive conceptions about motion that students in various cultures bring to the physics classroom.

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 student 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.

Another goal for teachers is understanding how new experiences and ideas can be designed to help students make sense of their physical world. Cognitive research emphasizes that instruction is not simply telling students to stop thinking the way they have been and think according to the example of the teacher, text, or some other authority. Note that the discussions in this lesson are rooted in common, concrete experiences. When phenomena come from everyday experience, they are more difficult to deny. Students respond better when information is linked to something they've experienced rather than to a pronouncement from authority.

Several additional kinds of research influence this lesson. Research on verbal interaction in the classroom helps me to define the climate that fosters concept development. Related areas of investigation, such as brain research and learning styles, are mentioned in passing largely because, in my experience, they appear relevant. Their actual relation to concept development is yet to be understood in an operational sense.

This first lesson is presented below as a transcript interspersed with text that explains the research-based rationale behind the instructor's decisions. The teachers's primary goal is to give students an idea of the content in the unit on the concept of force. While being open to and accepting of what students say, the teacher attempts to help students clarify their initial ideas about force. Also, the teacher assesses students' understanding of related ideas and builds the semantic network of ideas the unit activities should uncover. Thus, the curriculum is not predetermined but can be built, depending on conceptual and rational needs and, to some extent, the contexts of interest of the students.

Teacher: *Today we are going to try to explain some rather ordinary events that you might see almost 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.*

Students' views of the physical world, although valuable in their daily world, differ from the scientists' views of the world (Driver 1983, Gilbert and Watts 1983).

Teacher: *A key idea that we are going to use is the idea of force. What does the idea of force mean to you?*

(A discussion follows. My experience suggests that the teacher should allow this initial sharing of ideas to be very open.)

To students, the word *force* has multiple meanings (Viennot 1979). Typically, they suggest it means something to make something happen, to create change (Minstrell and Stimpson 1986). Their descriptions often include related words: energy, momentum, strength, fast moving, or a hit (Osborne 1984). The terms "push" and "pull" usually are mentioned. Often, discussion stops at this point and the class moves on with both students and teacher believing they have a common understanding of the term. But contrary to the scientist's conception, students believe that the push or pull must be due to some causal agent. This agent, in their view, makes things happen; it is the motivator or the energy source in the situation (Minstrell and Stimpson 1986).

Teacher: *You've mentioned words that represent many ideas. Most of them are closely related to the scientist's idea of force, but they also have meanings different from the scientist's ideas. Of the ones mentioned, probably the one that comes closest to the meaning the physicist has is the idea of push or pull, so we'll start with that. We'll probably find out that even that has a slightly different meaning to the physicist. (The teacher should allow the class to begin with this meaning for force rather than present an elaborate operational definition.)*

Through the course of events in the classroom, the students' ideas will evolve. Lessons have specific purposes, so students gradually differentiate and then recombine their initial ideas into a view that is more logically consistent when applied across a broad range of situations. For example, certain lessons will help students integrate passive support by a table and active support by a hand under the same general concept of force (Clement 1987, Minstrell 1982b). Students will learn to differentiate actions like force, impulse (force x time), and work (force x distance) from each other and from properties (or states) of objects or systems—properties like velocity, acceleration, momentum, and energy (McDermott 1984, Minstrell and Stimpson 1986). The resulting conceptions will probably be more like the scientist's, and they will have grown out of pieces of knowledge that make sense to students (diSessa 1987).

Teacher (dropping a rock): *Here is a fairly ordinary event. We see something like this happening every day. How would you explain this event, using your present ideas about force?*

The teacher picks an ordinary occurrence, which is preferable to a special situation for instruction. If we choose ideal case situations, especially in physics, we run the risk that students will think of physics as episodic, dependent on specific situations, and separate from daily experiences with the physical world. Instead, students should consider physics in the context of their everyday lives. Part of the value of the formal ideas of physics is that they apply consistently across common phenomena.

Teacher: *Don't speak right now. I want each person to have a chance to do his or her own thinking.*

To the extent possible, the teacher actively engages each student in the activity. Students have a vested interest in the outcome of the activity if they have first committed themselves to it (Minstrell 1982b, Rowe 1974).

Teacher: *Make a drawing of the situation and show the major forces acting on the rock when it falls. Use arrows to represent the forces, and label each as to what exerts the force.*

The teacher encourages students to represent the situation. Popularizers of brain research, like Buzan (1974), believe that representing situations with pictures as well as words activates the visual and verbal parts of the brain. It is suggested that this enhances access to knowledge by creating linkages to more parts of the brain. This makes sense to me as an experienced teacher and learner. If people have recorded their ideas on paper, they are less likely to deny the existence of their initial ideas and they are more likely to notice inconsistencies between their original idea and what actually happens (Loftus 1980).

Students (naming the forces they have represented):

Gravity by the earth

Weight of the rock.

Both gravity and the weight.

Many students think of weight as a property of a body and have not conceptualized the weight of a body as the force on that body exerted by the earth, basically a relationship between the object and the earth (Carey 1987).

Student: *Air*

Some students mean air pressure in the downward direction. Air pressure is apparently not distinguished from gravity (Minstrell 1982a). For others, air is the main effect that makes the weight of the object, and the gravity effect is just 1/6 the weight, i.e., the residual left after air is removed. This was apparently deduced from the fact that on the moon things weigh 1/6 of their weight on the earth (Jung 1984). (The relation between gravity and air pressure is the subject of another lesson and not presented in this chapter.)

Students: *Resistance.*

Friction.

Resistive force, while common to everyday experience, involves rather complex mechanisms. To many students, friction does not act in a particular direction. It is somehow just present in situations (Clement 1987). Due to the complexities of both the scientist's and the students' views, the instructor decides not to center the discussion around this idea until some more basic notions about force are clarified.

Students: *The spin of the earth*

Nuclear forces.

Since many of these ideas are complicated and rely on a more basic understanding of force, the teacher attempts to limit the discussion.

Teacher: *Which of these is the major force, or which are the major forces acting on the rock while it is falling?*

Students: *Its weight.*
Gravity.

If the weight/gravity relation hasn't been developed in an earlier unit, this would be a good opportunity to do so (Champagne, Klopfer, Solomon, and Cahn 1980).

Teacher: *Actually, weight is the name we give to the gravitational pull on an object near the earth. So, weight and gravity really represent the same idea. Let's take this as an assumption for now. We really should come back later and develop that more fully.*

Sometimes the teacher needs to make the choice to state a piece of information and ask students to take that as a basic assumption, so the argument can continue. That is what the teacher does in this instance. But if the distinction was developed earlier in class, the students could now be encouraged to briefly review those arguments. Teaching experience suggests that the use of earlier arguments helps students make them part of their general long-term knowledge (Minstrell 1984). Learning research supports that experience (Buzan 1974).

Teacher: *Is the falling rock moving at a constant speed, or is it speeding up or slowing down? How do you know?*

The students have had prior class experience discriminating between constant or uniform speed on the one hand and changing speed on the other. This lesson provides an opportunity for the teacher and students to revisit the arguments for separating those motions. While one of the main objectives of a later lesson will be to differentiate the force acting on the object from the resulting action of the object, the teacher introduces that idea here by asking about the motion as a separate question from the forces. Also, it is important to have students attempt to justify their inferences as well as make them. "How do you know?" "How did you decide?" "Why do you believe that?" These are all useful examples of justification of knowledge questions (Arons 1983, Minstrell 1987). The teacher should allow several seconds to pass before calling on students or allowing them to answer so everyone has an opportunity to develop an answer. Rowe (1974) calls this period "wait time."

Student: *The same speed all the way because I saw a film where some guy said that all things fall at the same speed.*

The teacher pauses here for three to five seconds before commenting or calling on another student so the first student can evaluate her answer (Rowe 1974).

Student: *No wait, that's if two things fall, they both fall equally fast. I don't know. (More wait time.)*

Student: *I think the rock speeds up.*

Teacher: *What evidence do you have that makes you think it accelerates?*

Student: *The higher you drop it from, the harder it hits the ground or whatever.*

The teacher allows more wait time here, too. Even if students' answers are consistent with the scientist's view, give them time to evaluate their own ideas to decide their validity. The sources of validity should be experience, both informal and experimental, and logical, rational argument, but not the authority of a teacher or a text.

Student: *Also, when one of the groups was studying velocity and acceleration, they dropped a thing and it accelerated.*

Teacher: *So what would a diagram of forces look like to explain the falling rock?*

Student: *Just gravity or whatever down and a little bit of air all around the rock. Like this, I think.*

Student: *There are some of those other forces, but probably the gravity or weight pulling down is the main one.*

Teacher: *Suppose I make the rock speed up slowly in the upward direction, while keeping it in my hand. What are the forces that explain this situation?*

Student: *The hand making the up force.*

Teacher (after about five seconds wait): *Are there any other major forces in this situation?*

Student: *Well, yeah, the weight is still there. That's in the down direction, but the hand force has to be bigger.*

Teacher: *Do others of you agree with her analysis? Anybody disagree?*

Students: *Seems okay.*

Teacher: *How do you know the hand force must be bigger?*

Student: *Because it goes in that direction, up.*

Student: *If you want something to go in some direction, you have to put a force on it in that direction?*

Student: *You have to put a bigger force in that direction than in the other direction.*

Teacher: *While this rock is speeding up in either direction, the force in that direction needs to be bigger than all the forces in the other direction put together. Is that your idea so far?*

The teacher guides the students to clarify more specifically what they are suggesting. Since the pre-course conception of "force of motion" is probably stronger than their conception that "passive objects exert no force," the teacher may elect to take up forces on static (stationary) objects first.

Teacher: *During the next several days we will look more closely at the idea we call force. Many of the ideas you've suggested today will be useful, but we may also find that we will want to change some of our notions about force to make them more consistent with the phenomena.*

Additional Lessons: Integration and Differentiation of Ideas

The following examples concern several conceptual difficulties that the teacher can help science students overcome by carefully designing classroom instruction and interactions. The first lesson is designed to help students integrate their existing knowledge with new concepts and make its organization in memory more efficient.

Integrating Concepts of Force

Sometimes students are more parsimonious with conceptual knowledge than they need be. Rather than applying a certain concept or interpretation generally in various contexts, they apply it selectively. Research on students' conceptions of force suggests that they make a big distinction between objects they consider to exhibit active actions such as push or pull and those they see as agents of passive actions such as support or blocking. The active actions they definitely call force, but the passive actions do not count as force (Driver 1983, Minstrell 1982b). The main objective of this lesson is to make a reasonable case for classifying both active and passive actions under the same conceptual heading of force.

> **Teacher:** *Suppose we put this rock on the table. The rock is not moving; it is at rest. What are the forces acting on the rock in that condition? How do you decide? I want each of you to draw and write your own best answers. What makes sense to you? We'll share our answers in just a few minutes.*

When students' ideas are recorded on paper, it is easier for them to identify inconsistencies—and not so easy for them to ignore them.

> **Teacher:** *Okay. Now, I'd like people to share their ideas. What are the forces involved?*

Students usually suggest gravity or weight is a downward force acting on the rock. While some students suggest there is an upward force by the table, there is considerable argument whether a passive object like a table can exert a force. Virtually all the students believe the table is supporting the book, but their notions about force involve something much more active. Since force is a conception invented by humans, the students' ideas cannot be demonstrated to be wrong by performing an experiment and collecting data. The teacher must attempt to guide the students to scientists' rationale for the concept of force, which includes passive actions.

After establishing that the intellectual argument centers on whether it seems reasonable to think of a table as exerting an upward force, the teacher moves to another situation, the rock at rest in the outstretched hand. Nearly every student believes the hand needed to exert a force (Minstrell 1982b). Clement (1987) suggests this is one of those universally believed ideas that can be used as an anchor to build an analogical bridge to the "target situation" (the rock on the table). The hand clearly supports the rock, and students also agree that the hand exerts an upward force.

The teacher then invites the class to consider other examples between the commonly agreed upon anchor situation (rock on the hand) and the target situation (rock on the table). For example, the rock might be placed on, or hung from, a spring. It appears that observing the adjustments of the spring to the downward force exerted by the rock is enough to convince the students that the spring also exerts an upward force on the rock, similar to how the muscles in the arm support a rock on a hand.

Some of the students are beginning to ask their own questions about their understanding and that of their fellow students. Research suggests that before students go through conceptual change, they need to see that the new conception is plausible (Posner, Strike, Hewson, and Gerzog 1982). Some seem swayed by logical necessity or convinced by juxtaposing several similar situations (i.e., the rock is at rest and is supported by something in all instances). To these students, that is sufficient for them to invoke the following argument: For the same effect (at-rest condition), we would invoke the same explanation (downward force balanced by upward force). Other students need assistance to see that all the situations are similar (i.e., objects at rest). Some are more influenced by arguments dealing with the physical mechanisms that illustrate how the rock on the rigid, "immovable" table is similar to the rock on the bendable spring. The table, like a stiff spring, will definitely flex, and the amount of bending depends on the weight of the rock.

Teacher: *So, it would appear that even nonliving things that seem rigid do bend ever so slightly. We've observed this ourselves. Because scientists want to be logical and explain the same effect, at rest, with the same reasoning, then all three—the hand, spring, and even the table—are said to exert an upward force. The hand is very active. The table just exerts the force passively, because it happens to be in the way. By these sorts of arguments, scientists have come to believe forces are exerted by active and passive objects. In fact, they believe anything that touches an object must exert some force on the object.*

One of the teacher's main goals for this lesson was to integrate the concept of passive support under the broader concept of force. Students had a notion of passive support, but it was separate from their concept of force. The lesson helped students reorganize initial ideas into a more integrated and logically consistent structure. As a result, the students acquired a more encompassing meaning for the term "force."

Differentiating Related Ideas

Sometimes students have nearly the opposite conceptual difficulty: They use one technical term to encompass too broad a range of meanings. Rather than ignore this problem or simply tell students formal definitions of terms, the teacher can design instruction so students differentiate meanings and organize them into a more powerful arrangement. Consider a lesson directed toward helping beginning physics students differentiate the ideas of force and motion.

The teacher might start with a pre-instructional quiz to identify students' ideas about two situations: a low-friction cart moving at a constant speed across a tabletop and the same cart accelerating uniformly across the tabletop. On quizzes given before instruction, most students explain the acceleration of the cart motion by an increasing force, and they explain the cart moving at a constant speed by a constant "force of motion" in the forward direction. These notions are consistent with daily experience; if we want something to move with a constant velocity, we need to provide a constant push. For naive students, this motion implies force. Whenever they observe or read a description of a moving object, they link a force with the object. They don't really differentiate between the motion of an object and the forces that produce it. They do not differentiate the condition of the object from the actions that caused the condition.

To address the students' conceptual difficulty, the teacher may have them do an experiment where they must consider the two ideas. Students observe both the motion of a cart and the readings on a spring scale that monitors the pulling force. While noting that the cart accelerates across the table, students are surprised to observe that the force-scale reading stays constant. Their conception of a "force of motion" is so strong they will deny the validity of their experimental results. But faced with similar evidence from other groups, they begin to doubt their initial conception and search for resolution. They begin to separate the force acting on the body from the condition of motion of the body.

Then comes the more difficult question: How do we explain forces on an object moving with a constant velocity? Students have great difficulty coming to the logical conclusion that, to explain the constant velocity of the object in motion horizontally, the horizontal forces must balance each other (Minstrell 1984). To effectively change students' intuition and to have the learning transfer to multiple contexts, they need several more experiences with applying the balanced forces idea. It also seems to take periodic opportunities to repeat the rational arguments used to derive that conclusion.

Teacher: *If we explain the constant acceleration situation with constant net force, what do we do to explain the constant velocity situation?*

Student: *Maybe that just requires less extra force.*

Teacher: *But what happened when we had more or less force in the experiment?*

Student: *We got more or less acceleration.*

Student: *Maybe a constant speed situation could be explained by a constant decreasing force.*

Student: *But we saw that when we had more unbalanced force we got more acceleration, and when we had less unbalanced force we got less acceleration, but we always got acceleration.*

Student: *That's right, but it can't be an increasing force either. That wouldn't make sense.*

Student: *If it can't be constant unbalanced force, and it can't be decreasing force, and it can't be increasing force, what's left? No force?*

The students' laughter illustrates the absurdity of this conclusion (correct from the physicist's view). But to some, the empirical result from the experiment and the logical conclusion from the discussion are beginning to make sense. Yet they still question the value of this idea in the everyday world.

Student: *What about the car? You put your foot down a certain amount on the gas pedal and the car speeds up to a certain speed and then tops out for that pedal setting. If you take your foot off, the car slows down. If you push down farther, it goes faster. That seems like the faster you want to go, the more force you need.*

Students can now use the teacher's guidance and encouragement to analyze the situation involving an accelerating car. The teacher might get them to draw diagrams of the forces on the car at rest, speeding up, at a constant velocity, and slowing down. This is an opportunity for students to use skills and ideas from earlier lessons to identify forces acting on objects in various circumstances. By recalling what they know from earlier class experiences and reviewing the kinds of argument used to arrive at conclusions, they can springboard to a different situation. True, it often is a struggle for beginning students to differentiate between the ideas of force acting on the car and the resulting motion of the car. However, with careful structuring of observational experiences and discussions, the teacher can help students differentiate between related ideas.

Throughout science instruction, there are numerous examples of lack of differentiation by students. For instance, they do not differentiate area from perimeter or volume, or weight from density, size, mass, and volume. To build clearer understanding of science ideas, we need to deliberately design instruction to confront several related ideas, rather than simply tell what each idea means separately.

Summary of Instructional Principles

The two previous sections illustrate how research on cognitive processes and related areas can guide instruction. In this section I want to pull together some of the more important principles from cognitive research that affect science instruction, specifically restructuring knowledge, instructional design, and classroom environment.

Restructuring Knowledge

For many science teachers familiar with the findings of cognitive research, restructuring students' existing knowledge has become the principal goal of instruction. This commitment stems from the realization that the minds of students entering science classroom are far from blank slates concerning phenomena in the physical world. In physics and in other subjects dealing with day-to-day existence, students come to the classroom with strong initial conceptions (McDermott 1984, Driver, Guesne, and Tiberghien 1985). If instruction does not deal with many of these conceptions, students leave class without having appreciably changed their ideas (Goldberg and McDermott 1987, Minstrell 1984).

As illustrated in the preceding lessons, students' initial concepts are often very different from what we want them to learn. For example, their conception of force involves pushes and pulls by active agents but not by passive ones. Since motion may affect what happens in a situation, students consider it to be a force. To the scientist, motion is a condition or a state of an object, better described by concepts of velocity, momentum, and kinetic energy than by force, which the scientist considers an action on the body. This example suggests that many student ideas are not wrong, but they lack conceptual differentiation and integration. Student knowledge may be constructed from observational data that are similar to scientists' knowledge, but the structures organizing the knowledge are different.

An interesting research question asks: "At what level does one look for a conceptual thought unit?" McCloskey (1984) has represented student thinking about motion at the theory level and suggests it is similar to the impetus theory, an early theory of mechanics. Halloun and Hestenes (1985a, 1985b) center their search at the level of formal physics principles, like Newton's third law. From these perspectives, many student conceptions can be considered wrong. I focus on key words of situational attributes that the student emphasizes, from which student answers can be predicted (Minstrell and Stimpson 1986). This suggests that students may focus on problem features like activity/passivity, causal agency, and motion. DiSessa (1987) searches behind students' words for what he calls "phenomenalogical primitives." His focus is on constructs based on readily observable phenomena, such as observations of springiness in objects that lead students to classify events in the world as "spring-like."

Consider one more example of basically sound elemental ideas leading to a generally faulty conclusion. From everyday experiences, students come to believe that bigger objects have a bigger downward force acting on them than do lighter objects. Students also argue from the experience of pushing boxes around that if you put a bigger force on an object, it will go faster. Therefore, they conclude that since the heavier object has a greater push downward on it, it falls to the ground in less time. Each piece of knowledge is sound; the logic is sound. Yet this structuring yields the incorrect conclusion that heavier objects fall faster. In this case, there is one more relevant experience that needs to be incorporated: When pushing two boxes that you want to speed up equally, you will need to push the heavier one with a proportionately larger force. Thus, the student's argument, missing one piece, leads him to an incorrect prediction.

As science teachers, we need to decide whether we are going to define students' pre-instructional thinking according to historically developed theories and principles or according to student-described, salient features of phenomena. That decision dictates whether the instructional goal is to produce conceptual theory revolution or to restructure students' use of present knowledge and vocabulary for representing existing knowledge structures. In my teaching, I take the latter approach.

In some cases, students are simply unaware of particular phenomena, in which case the goal of instruction may be to extend their knowledge base. Without any previous exposure to particular phenomena, students seem to organize their observations according to conceptions from other contexts that they perceive to be relevant or analogous. In this chapter, I have focused on two kinds of conceptual transformation that learners go through in the process of restructuring their knowledge. One is knowledge differentiation, which involves splitting apart pieces of knowledge from what initially appeared to be one idea. The second, conceptual coalescence, is the integration of what initially appeared to be separate knowledge pieces into one idea. Just as these processes have been important in the development of ideas through the history of science, they appear equally important in the development of students' knowledge (Carey 1987).

Instructional Design

Cognitive research suggests that certain lesson designs can foster the growth of students' knowledge and understanding. Osborne and Freyberg (1985) have summarized the research on features of instruction that foster conceptual development. In the lessons presented earlier, there was a preliminary phase where the teacher and students identified students' existing ideas. This information might also be discovered through a diagnostic test at the beginning of the course or in a short pre-instruction quiz at the beginning of a unit or just before a major conceptual restructuring activity. Second, there was a focusing phase for students and teacher to clarify the students' initial ideas. This focusing usually takes place during a discussion after students record their initial ideas. The third phase involves an activity or situation that challenges the students' initial ideas. In the "at-rest" lesson, the book on the hand, the book on the spring, and the springy nature of the rigid table constituted the challenge. In the moving cart situation, the challenge came from the laboratory activity that presented results contrary to the students' predictions. Finally, there is an application phase, when students have the opportunity to practice using the new idea in multiple contexts. For our lessons, students needed the opportunity to explain the "at-rest" condition by examining significant horizontal forces when objects are at rest in air, on water, or on an incline. Students needed to be able to explain common moving situations, such as the car accelerating and then moving with a constant velocity, all with the same throttle setting.

Students also need to recycle through the arguments for and against the need for a forward force in later contexts, such as projectile motion and circular motion. The new ideas or restructuring of ideas will need expanded contexts of application. Some students will demonstrate transfer to the new situations; others will revert to previous conceptions. The percent of students successfully transferring to new situations increases with each new episode. The new conceptions are never adopted by all students after only one context, and it is probably unreasonable to assume that the whole class will make the transfer.

In addition to general guidelines for instructional design, research has given us a better understanding of the limitations of perception. Attention is very important. At the beginning of a lesson, we need a question or activity that is thought-provoking or will arouse the learner's curiosity. The use of pre-instruction questions, especially those that ask students to make a prediction that can be readily tested, stimulates interest in subsequent related activities (Jung 1984). Although Bates' (1978) review of the literature, dealing with the value of the laboratory in promoting understanding, found no positive influence, I believe that laboratory activity does have a significant effect if it directly relates to students' initial ideas and allows them to test those ideas (Minstrell 1984). But if the activity is viewed as just one more in a series of unrelated episodes at school, students are not likely to make the connection at all.

It is important to encourage students to seek, identify, and resolve inconsistencies between their ideas and what actually happens in the laboratory or demonstration activity. In the second example lesson, students were asked to compare their explanation for the rock at rest on the hand and on the spring with their explanation for the rock on the table. Aren't all these situations the same? If so, shouldn't all the explanations be similar? If so, how? In considering the forces on the moving cart, some students needed to be guided to notice the difference between their initial ideas and what happened in the laboratory activity. Some lacked respect for their empirical methods and results, and preferred to believe their initial intuitions. They had to be encouraged to check their results with others and then to resolve inconsistencies.

In the classroom, we should strive for transfer as a measure of understanding. Pea (1988) suggests some of the sorts of transfer that can help define understanding. We want to ensure that what students learn in the formal learning context is transferred to everyday life and work situations. In the class discussion during the lesson on forces on moving objects, the teacher encouraged students to consider a common experience: a car speeding up. Students also should have opportunities to acquire and apply knowledge in an integrated manner that approximates the demands of problem solving in everyday life. In the lesson discussion, the newly hypothesized idea about force and previously acquired knowledge were brought together in the common, but complex, situation of the car on the roadway. The teacher did not leave students with only an understanding of the laboratory situation with carts on tables. Conversely, the concepts, skills, and strategies that students have acquired and used effectively outside the school setting should be brought into the classroom and applied to formal learning to demonstrate the value (and limitations) of experience. In the car situation, many of the ideas students brought with them were useful (e.g., wheels spinning on a frictionless surface will not make the car go, a hand out the window feels progressively greater resistance with an increase in speed, and the car's speed does top out if one holds the gas pedal at a certain position).

Finally, students should be able to go beyond the problem originally learned in the classroom and solve related problems, moving in a series of steps to problems that are increasingly different from the learned problem. The key ideas and thinking used in the sample lesson should be evoked again in subsequent contexts, such as a car coasting to a stop or a box sliding to a stop.

To teach for transfer of ideas, we need to include activities requiring students to use new ideas in multiple contexts. To do this we need to offer subsequent contexts, at appropriately spaced time intervals, where students can use the same arguments used in developing the new idea. For example, in the context of the forces on moving objects, students can be asked to explain, perhaps two weeks later, the motion of horizontally launched projectiles. What are the forces acting on the rock after it has left the hand? If the idea of force has been separated from the condition of motion of the object, then students should be able to identify gravity, and perhaps air resistance, as the only significant forces in this context.

Classroom Environment

Teachers need to create an appropriate climate for fostering development of understanding. That climate should encourage questioning. Questions asking for predictions, for clarification of meaning, for justification of how a student decided a particular answer, and for interpretation, explanation, and observations, should prevail. Between questions and answers, as well as after answers, the teacher should allow three- to five-second intervals of wait time to encourage more thoughtful responses (Rowe 1974). There should be an atmosphere of mutual respect among students and between students and teacher. Students bring their ideas into class; since these are the ideas out of which their new ideas will be constructed, the sharing of those ideas should be respected.

Finally, time is a critical factor in developing understanding. There should be enough time within lessons for the inconsistencies illustrated by a new experimental result to register. We must provide the time students need for mental restructuring. Hurrying on to the next lesson or the next topic does not allow for sufficient reflection on the implications of the present lesson. We have found that physics teachers typically spend one to three days developing Newton's laws and the remainder of a two- to three-week unit doing exercises to practice them. When about five days were spent carefully developing the ideas, and even though students didn't get as much practice in manipulating equations, their understanding of the critical ideas at the end of the first or second semester was significantly better, both statistically and educationally. With more careful and extensive development time, more than twice as many students are able to answer difficult conceptual questions (Minstrell 1984).

With an understanding of the research, teachers and developers of curriculum or instruction can be more analytical in their attempts to meet students' needs, better understand why lessons succeed or fail, and gain insight as to what to do or not to do next time.

As a teacher, I would encourage other teachers to become involved in research related to the cognitive processes of their learners. I predict it will enliven their time in the classroom, as it has mine. I also predict it will enhance students', and perhaps their own, understanding of the natural world.

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8

Research on Teaching Scientific Thinking: Implications for Computer-Based Instruction

Jill H. Larkin and Ruth W. Chabay

Recent research on teaching scientific thinking is already being reflected in practical, computer-based instructional programs. While some of these programs were intentionally based on the research, most of them have been developed independently. The research, however, is providing us with a useful guide to the characteristics of effective instructional programs.

We first summarize in this chapter the central findings of cognitive and motivational research relevant to teaching science and then consider the merits of four computer-based programs for science instruction. We also suggest characteristics of appropriate and effective software for teaching science. (For a more general review of available instructional software in science, see Klopfer 1986. The appendix in that paper and Imhof 1988 include information about microcomputer-based laboratory [MBL] software and other current developments that use computers in science teaching.)

Knowledge Behind Scientific Thinking

Two strands of research characterize the difficulties in learning science. The first contrasts expert and student problem-solving behavior. Students (especially those getting high grades in the physical sciences) seem to work in a mental "space" of equations, trying to remember suitable equations and put them together accurately. In contrast, experts spend much of their problem-solving time in a mental space of scientific reasoning: They talk qualitatively of forces, momentums, velocity changes, and the relations between them, without ever writing an equation (Chi, Feltovich, and Glaser 1981, Larkin 1981, Larkin 1983, Simon and Simon 1978).

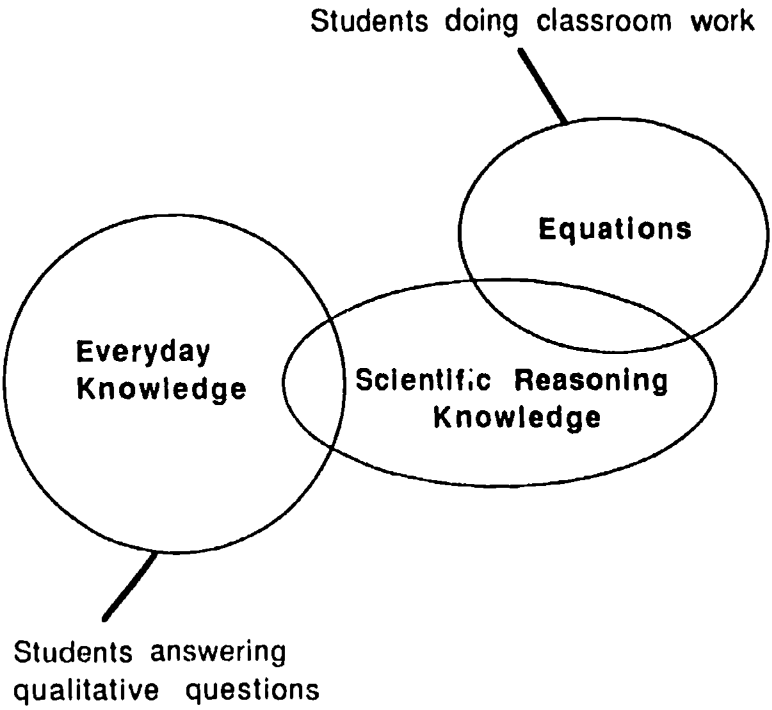
The second strand of work concerns the nature of everyday knowledge students and the general public possess of phenomena in the world. This knowledge is perfectly adequate for daily living, but it conflicts in some important ways with modern theories of physical science. For example, when asked to explain the motion of a coin tossed in the air, most people (including, unfortunately, those who have taken physics courses) say something like this:

> The push (or force) of the hand makes the coin travel upward, until this force wears out and gravity takes over, pulling the coin back down (Clement 1982).

As suggested in Figure 8.1, these two strands of research are complementary. All of us begin with everyday knowledge. Courses in the physical sciences are effective in teaching equations in part because students have other experience with equations. But science courses seem ineffective in teaching the powerful reasoning strategies that characterize the discipline. Therefore, good students put aside their own qualitative ideas about the world and rely on equations. But when pressed with qualitative questions, they cannot draw on their equation knowledge and must fall back on their naive qualitative ideas. Other students who cannot put aside their original qualitative understanding of the world become hopelessly confused by the demands of learning science (Trowbridge and McDermott 1980, 1981).

A central question for effective science teaching is: How can we teach better scientific reasoning, allowing our students to do more than observe phenomena, push equations, and flounder in inconsistencies between everyday knowledge and the reasoning of science? The last 10 years has seen considerable theoretical progress on this question, resulting from precise and extensive analyses of (1) the

Figure 8.1
Kinds of Knowledge
Used in Scientific Reasoning

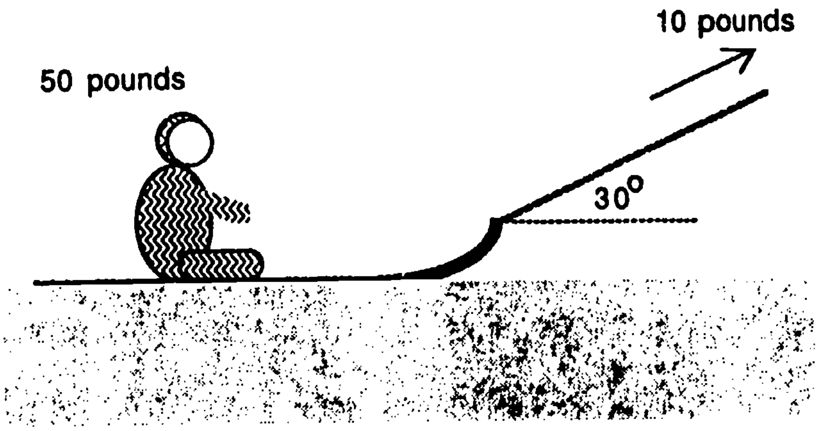


nature of scientific knowledge, and (2) the contrasts between everyday, scientific, and equation knowledge.

The Nature of Student Knowledge

Effective use of research contrasting students' and scientists' knowledge has come from developing precise models of these two kinds of knowledge. To see how these models work, let us consider two typical solutions—one by a good student, the other by a good physicist—to the following simple mechanics problem:

> A girl pulls a sled at constant speed along a horizontal surface, using a rope making an angle of 30° with the snow surface. The sled carries her little brother, and the sled and brother together weigh 50 pounds. If the girl is pulling with a force of magnitude 10 pounds, what is the coefficient of friction μ between the sled runners and the snow surface?



A moderately good student's solution might look something like the following.

> To find the coefficient of friction μ, I need an equation with μ in it. The one I know is $f = \mu N$.
>
> Now, N in that equation is the normal force. The normal force is usually equal to weight, which here is 50 lb. So $f = \mu \times 50$.
>
> Now I need to find f. Well, f is a force and we have a pulling force of 10 pounds. So $10 = \mu \times 50$ or $\mu = 50/10 = 5$ is the answer.

Although a physicist will quickly spot a fundamental error in this "solution," let us try to understand how the student may have constructed it and how and why errors like this are so common.

The student begins work with an initial set of knowledge described by the sentences in the problem and by the accompanying diagram. Cognitive science commonly calls this beginning set of knowledge the "initial state," distinguishing it from later states in which the individual has a different set of knowledge. The student also has some knowledge about how to recognize when he has finished the problem or reached a "goal state." For this student, a goal state is probably any situation containing a plausible sequence of algebraic manipulations of physics equations that (1) use the values given in the problem statement and (2) lead to a numerical value for the requested quantity (here the value of the coefficient of friction μ).

Finally, the student has knowledge of things that can be done to develop new information about a problem. If we call these things that can be done "operators," then solving a problem can be described as choosing a sequence of operators that starts with the initial knowledge state and develops it into a satisfactory goal state. The operators used by our hypothetical student seem to be:

1. Apply operations from algebra and arithmetic.
2. Write down any equation learned from the physics textbook or lecture.
3. Substitute for a symbol any value or expression that is anywhere stated to be equal to the same symbol, or approximately the same symbol.

Because these operators are concerned only with equations, symbols, and values, the student's initial knowledge state (S_i) can be characterized by the symbols, values, and relations in the problem statement:

S_i = {(angle = 30°) (weight = 50 pounds) (force = 10 pounds) (μ = ?)}

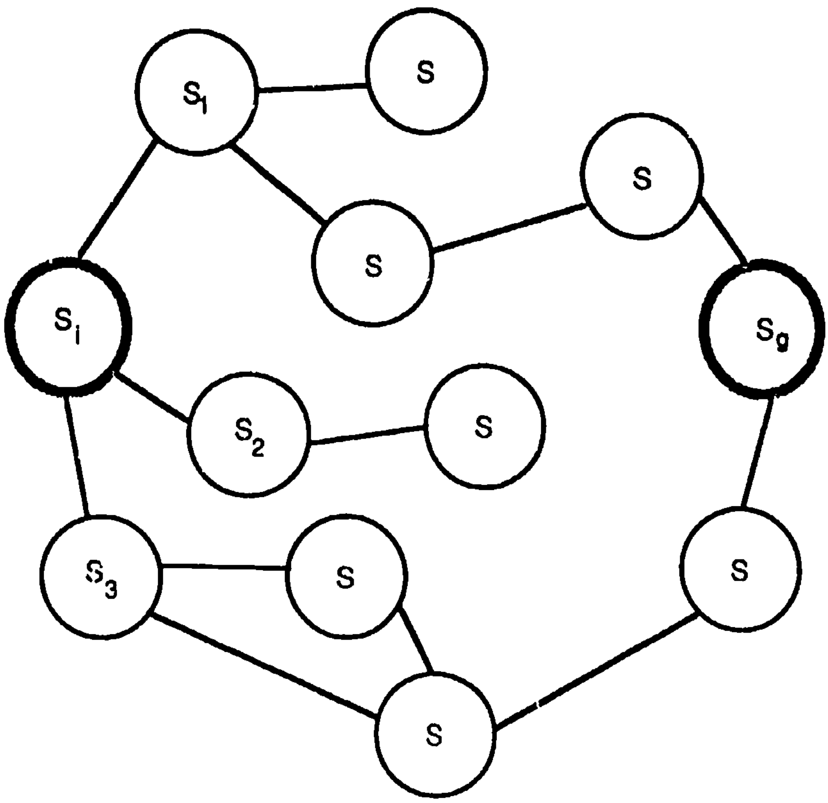
But now there are many operators the student might apply. "Sin 30° = .5," "weight = mg," "f = μN," and "50/30 = 1.4" are all relations from physics or mathematics that use some of the information in the initial state. After any one of these operators has been used, there is a new knowledge state that includes the knowledge from the original state and the new information that has been added. At this point a similar choice problem arises: What operator will be applied next?

This model of problem solving is commonly represented by diagrams like Figure 8.2. The problem solver begins in a knowledge state S_i. Each operator is represented by a line. Depending on what operator is selected, the solver moves to knowledge state S_1, S_2, or S_3. In each knowledge state, further operator choices are necessary. Finally, if an appropriate sequence of operators has been chosen, the solver reaches the goal state S_g (or one of several acceptable goal states). In Figure 8.2, as is often the case, there is more than one way to reach the goal.

Now we need to ask how our hypothetical student selects among the available operators. The following method is common among students who get good grades.

1. Begin by writing a physics equation involving the desired quantity.
2. If a single symbol (or two very similar symbols, such as f and

Figure 8.2
Problem "Space" with Knowledge States (labeled S) and Operators (lines)



F) appear in the problem state, then consider them equal and substitute the value or expression for one into any equation involving the other.

3. If a quantity appears only once in the current knowledge state, and it is not the desired quantity, then write a new equation involving that quantity.

4. Repeat steps 2 and 3 until a value for the desired quantity is found.

This simple procedure corresponds exactly to what our hypothetical student did with the sled problem, and it describes the work of many real students. Better students are more sophisticated in distinguishing quantities (they would not confuse f in $f = \mu N$ with the pulling force), but their problem-solving methods are much the same. As suggested in Figure 8.1, student knowledge of physical science is equation or formal knowledge, divorced both from their everyday knowledge (e.g., of pulling sleds) and from the richer conceptual knowledge of scientists.

The Nature of the Scientist's Knowledge

Using the language of knowledge states and operators, how can we characterize more precisely the knowledge a scientist brings to solving problems? A physicist solving the sled problem might begin a solution in the following way.

> The key thing is that the sled (with the boy) moves at constant speed. That means there's no net force increasing or decreasing the speed of this system. So, in each direction, the forces on the boy-sled system must balance, yielding a zero net force. I can therefore separately add up the horizontal and vertical components of the forces on the boy-sled system and make them balance.
>
> In the horizontal direction, the forces are the horizontal component of force due to the rope F_{rh}, and the frictional force f. These forces balance, so $F_{rh} = f$.
>
> In the vertical direction, the downward force is equal to the weight of the boy-sled system (W). The upward force is a combination of the vertical component of the force due to the rope, F_{rv}, and the normal force N exerted on the sled by the snow. The upward and downward forces must balance, so $N + F_{rv} = W$. *[Note that the expert picks up a point that the student, simply juggling symbols, missed: the normal force alone does not balance the full weight of the boy and sled, because the girl is pulling up as well as forward.]*
>
> The frictional force f depends on the normal force N and the coefficient of friction μ. So $f = \mu N$. I can now combine these equations to solve for μ in terms of F_r and W. *[Note that the expert has not yet used specific numerical values for any of the quantities, but first solves the problem in general.]*

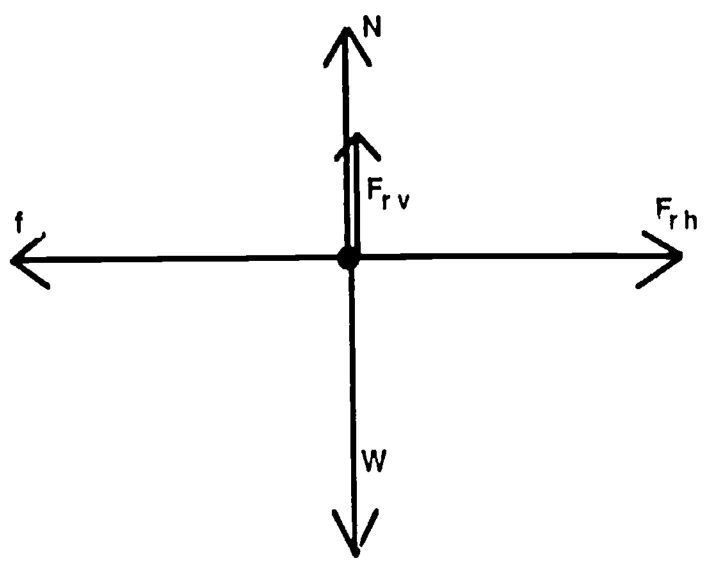
Even these initial statements suggest a very different solution process from that of typical physics students. What can we infer about the knowledge states and operators used here?

First, the scientist's initial state seems to be quite different from the symbol-quantity state characteristic of students. The physicist's initial state, for example, clearly contains the information that the sled's speed is constant and explicitly groups the boy and sled, calling them the "boy-sled system." Then, the physicist applies successive operators, which each add more information about the system.

The first operator applied adds the information that in every direction the forces on this system must "balance," or yield a net force of zero. The next operators add information about the forces in the horizontal and vertical direction. There is a very visual or spatial flavor to these comments, and physicist solutions often contain diagrams like that in Figure 8.3. These "free body" diagrams show the directions and rough magnitudes of all the forces on a system (here the boy and sled). Later operators interpret these balanced sets of forces as two sides of an equality. Only toward the end is there direct algebraic substitution of the kind that dominated the typical student solution. Like the student, the scientist has many available actions. Although the operators used by the scientist are different, they still form a problem space like the one shown in Figure 8.2.

The preceding example illustrates the following selection process that experienced physicists seem to use (Heller and Reif 1984, Larkin 1983).

Figure 8.3
"Freebody" Diagram Showing Balanced Horizontal and Vertical Forces on the Sled



1. Redescribe the problem, using scientific concepts. In the sled problem, these include system (the boy and sled are explicitly grouped as one system), force components, and constant speed.

2. Qualitatively relate the aspects of this description, checking for inconsistencies. In the sled problem, the unchanging velocity is checked against the inference that the forces must balance (or sum to zero) in every direction.

3. Apply one of the major principles of the science to write one or more central equations describing the problem. In the sled example, the major principle is that the forces balance in all directions (including vertical and horizontal).

4. Use other equations to substitute for unknown quantities so as ultimately to find any desired quantitative value. Only at this point does the more experienced solver's work begin to look like that of the beginner, in that equations and algebraic manipulation operators are used.

Although the details are different, other studies suggest that the general approach is the same in other sciences: Scientist and student thinking contrast in important ways. Scientists' problem solving starts with redescribing the problem in terms of the powerful concepts of their discipline (systems, balanced forces, constant velocity). Because these concepts are richly connected with each other, the redescribed problem allows cross checking among inferences to avoid errors. For example, Figure 8.3 immediately shows that the magnitude N of the normal force (due to the snow surface) must be less than the weight W of the boy and sled. In many situations these two forces are equal in magnitude, and a common student mistake is to equate them. A diagram or visualization like Figure 8.3 protects the solver against this error.

What Motivates Students to Learn?

Even if we can analyze in detail how experienced scientists solve problems, this is not enough to enable us to teach students how to solve the same problems. The best learning environments are still likely to be of little use if students are bored, passive, or resentful. A central pedagogical question, therefore, is how to motivate students to invest effort in problem solving.

Researchers distinguish between two kinds of motivation: intrinsic and extrinsic. Intrinsic motivation is the willingness to engage in activity for its own sake: for example, to read a book because it is interesting, funny, or exciting. Extrinsic motivation is the willingness to engage in an activity for external reasons: for example, to read a book because it's required to do a book report or to get a reward (such as a good grade). The characteristics of effective instruction require that the student be continuously and actively involved in learning. For this reason, extrinsic motivation (expectation of a reward when the task is done) seems likely to be less important than intrinsic motivation (factors keeping the learner involved moment by moment). Indeed, in some contexts, extrinsic rewards definitely undermine intrinsic interest (Lepper and Greene 1978).

Over the past 30 years, three separate theories of intrinsic motivation have been developed by researchers looking at people engaged in a variety of activities, from climbing mountains to solving puzzles. Each theory postulates one primary motivational factor: challenge, curiosity, or control. Additionally, each theory suggests that there is an optimal level of the motivating factor. Both higher and lower levels seem to decrease motivation.

Challenge promotes the desire for achievement, a sense of personal competence, or self-efficacy. In learning environments, students may be challenged when working toward specific achievement goals or when solving problems at a particular level of difficulty. Tasks that are too easy may undermine motivation by providing insufficient challenge, but tasks that are too difficult or too big may decrease motivation by causing frustration.

Control reflects a sense of self-determination, of feeling in command of the environment. A sense of control is increased if the learner is an active agent, directly doing the work and manipulations, rather than passively observing. Control is also increased by giving the learner choices. Students may be offered decisions as crucial as what tasks to attempt or how to structure a problem solution, or as peripheral as choosing the name of a pizza parlor or picking the color of a racing car in a mathematics game.

Curiosity describes humans' interest in exploring new things and their response to novel, surprising, incongruous, complex, or counter-intuitive elements. These things not only attract attention but intrigue learners, inspiring them to explore further or to try to resolve apparent paradoxes or incongruities. A repetitive, uniform, visually unvarying task quickly becomes boring. Too complex or novel a situation, however, may overwhelm learners so that they cease trying.

Features of Effective Instruction

Malone and Lepper (1986, Lepper and Malone 1986) have argued that the three primary motivational factors—challenge, curiosity, and control—work together to determine intrinsic motivation. Providing for challenge, curiosity, and control is entirely consistent with the cognitive concerns discussed earlier in this chapter, and it is an important goal in the design of effective instructional activities (Lepper and Chabay 1985).

In the last few years, several efforts in applied instructional research have produced dramatic gains in learning, on the order of doubling scores on individual tests or raising grades in a course by 20 percent (Heller and Reif 1984, Anderson, Boyle, and Reiser 1985, Palincsar and Brown 1984). Some of these gains are combined with substantial reductions in learning time (Corbett and Anderson in press). None of the subject matter that was taught was trivial or required rote learning; the studies involved geometry, physics, computer programming, and reading comprehension.

Although the models of student learning in these experiments vary in details, all share the following six features.

1. Develop a detailed description of the processes the student needs to acquire.

To be effective, these descriptions need to be very detailed (Heller and Reif 1984). Often, although not in every case, computers have often been used to build programs capable of doing the things we want to teach students. Computer-implemented models have two advantages. They keep rigorous track of all aspects of a description, however detailed, and they enforce completeness, because a computer program won't run unless it contains all the processes needed to finish a task. Whether or not the description is implemented on a computer, it gives the teacher or instructional designer a detailed picture of the knowledge to be taught. Instructional goals can then include enhancing intrinsic motivation for learning this specific knowledge.

Noting and acknowledging a student's progress can help sustain a sense of challenge. A specific analysis of the processes required for a task makes it possible to note detailed improvements in execution or choice of operations. The detailed analysis of the problem task also makes it possible to provide feedback specific to the student's errors. This helps the student avoid frustration by keeping her on a productive path to a solution.

2. Systematically address all knowledge included in the description of process.

Since the description of processes to be acquired is necessarily detailed, the corresponding instruction explicitly addresses a large number of individual knowledge units. As our earlier discussion of problem solving suggests, much of this instruction should deal with developing the student's ability to choose and use appropriate operators. To help students learn to select operators effectively, it is essential to give them practice in doing just that. Students should have control in constructing a solution, for motivational reasons and because learning to think requires practice in taking control and making choices.

By systematically addressing all the needed details of thinking, the level of control can be made appropriate. In well-designed instruction, able and well-prepared students quickly make many choices on their own. At the same time, less able students have access to much more detailed guidance.

Challenge can also be enhanced by specifying the goals for parts of a task. For example, the goal of redescribing a physics problem in terms of forces is more explicit and thus more appropriately challenging than the general goal of solving the problem by any means.

By guiding students to construct problem descriptions involving scientific concepts, it becomes possible to provoke curiosity about the multiple relationships between these concepts. For example, in our sample expert solution, it was possible to ask whether the forces adequately accounted for the motion of the sled. In contrast, the student solution involved only selecting and solving equations. Highlighting discrepancies in the student's solution (such as the fact that, in the preceding problem, the normal force exerted by the snow is not the only upward force on the sled) can awaken curiosity and lead a student to try to resolve apparent contradictions in thinking.

3. Let most instruction occur through active work on tasks.

Actively working on an interesting task allows the students to integrate the many knowledge units in their minds exactly in the form needed to address the task. Because this form may be different from that needed to perform simpler component or prerequisite tasks, it is necessary that the student work on full, complex tasks. As the student works, therefore, it is important to provide enough guidance and intervention to prevent confusion. In different studies, this is achieved by guiding the student's work with an externally imposed control structure (Heller and Reif 1984); by "scaffolding," doing part of the task for the student while letting him do what he can (Palincsar and Brown 1984); or by "model tracing," letting a computer program follow the individual steps of a student's work, intervening with diagnostic feedback when the student makes errors (Anderson, Boyle, and Reiser 1985).

From the beginning of the instructional sequence, the student has the challenge of constructing a solution to a complete problem and the control of choosing a strategy and proceeding as far as possible (with help provided as needed). A complete problem also provides more scope for curiosity. Students' feelings of control are enhanced by environments in which they can function as active agents—entering responses and constructing solutions—not just reading, listening, or pressing the "RETURN" key and watching text go by. The more directly learners can manipulate the symbols or objects (with a mouse or a touch panel, for example), the more they feel a sense of control. Learners must feel, too, that their actions influence the outcome of a task. If students sense that their choices and actions will make no difference in the flow and development of an activity, they are likely to invest little effort.

4. Give feedback on specific tasks as soon as possible after an error is made.

Working on complete tasks (rather than prerequisites or components) usually suggests activities with goals whose attainment is somewhat uncertain due to the size of the task or the level of difficulty. To optimize challenge and avoid frustration, there must be frequent feedback on performance and proximity to the goal. Such feedback is essential not only to correct errors but to give students a motivating knowledge of progress (Lepper and Chabay 1988). Regular feedback may also enhance students' sense of control by assuring them they are building on competent work. Moreover, when feedback is given soon after an error is made, students can more readily identify what piece of knowledge needs to be corrected.

5. Once is not enough. Let students encounter each knowledge unit several times.

Students must learn a large amount of material in detail. When teaching this knowledge, it is crucial to avoid overloading their capacity to pay attention. When this happens, they cannot attend to some information or make connections or inferences regarding the unattended material. Just as importantly, multiple exposures to the same knowledge units allow students to build confidence in their ability to use the knowledge increasingly well. This encourages them to set higher goals and tackle more challenging problems. Once knowledge has been used in one setting, its appearance in a new situation may also provoke curiosity.

6. Limit demands on students' attention.

If attention demands are not limited, the student's curiosity can be overwhelmed by too much complexity and diversity. An optimal level of complexity is more likely to be attained by keeping the current context simple enough that students have enough mental space to compare, contrast, and explore. Limiting complexity of displays and tasks reduces the number of frustrating errors due simply to overlooking some piece of information. The challenge should come from the substance of the task, not from managing an overload of information.

Examples of Science Software Programs

Computer-based instruction provides a unique opportunity to capitalize on the principles discussed in the preceding section. A computer program is ideally suited to systematically addressing all knowledge in a detailed description of all the processes required to perform a task. An interactive computer program can allow the student to work actively on the full task of interest and can provide detailed feedback soon after an error is made. A well-designed generative program can easily provide a large number of practice examples. A good computer display is clear, uncluttered, and dynamic. It guides the learner's attention to salient features of a task and appropriately limits attentional demands to avoid mental overload.

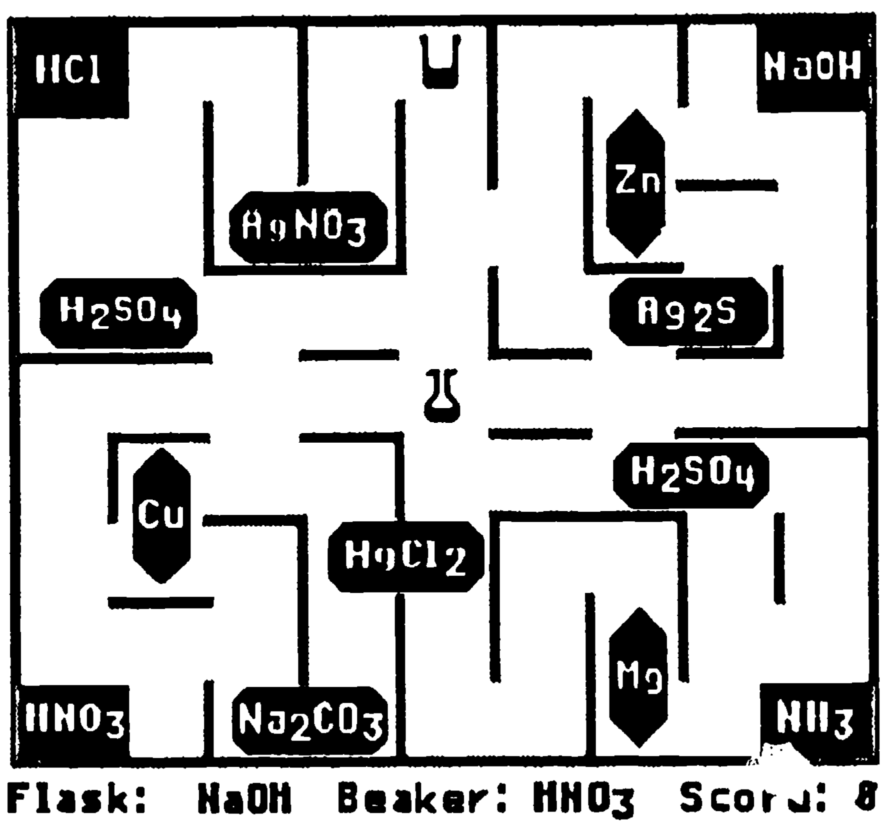
This section discusses four award-winning examples of software designed to teach scientific thinking. They are four very different kinds of instructional programs and do not represent the full range of software available or conceivable. The first is a game providing drill and practice. The second uses an automatically updated display as a central device to teach students the reasoning behind balancing chemical equations. The third provides direct instruction in solving word problems, and the last is an activity on relating graphs to the motion they describe. Our purpose is to illustrate and make explicit the principles of good instruction developed in the previous section and to show how these principles can provide guidance in the difficult task of assessing and selecting effective instructional materials.

A Game for Drill and Practice

Figure 8.4 shows a display from an educational computer game, CHEMAZE (Smith, Chabay, and Kean 1983-85). A student steers a flask filled with an acid or a base through a maze. The student's goal is to remove the obstacles (other chemical substances) from the maze by initiating chemical reactions with the reagent in the flask. Of course, not all of the obstacles will react with a single reagent, so the student must plan sequences of similar reactions that will eventually lead to one of the square "filling stations" in the corners of the maze, where the flask can be refilled with a different reagent. Points are won each time the student destroys an obstacle. Additionally, the hostile beaker at the top of the maze chases the flask. If the beaker's contents react with the contents of the flask, the game ends.

Figure 8.4
Display from CHEMAZE

(Smith, Chabay, and Kean 1983-85)



The knowledge being taught is the ability to classify substances according to their chemical properties (e.g., as acids, bases, metals, or insoluble compounds), and then to use this knowledge to predict what other substances they will react with. To pursue more complex problems and to understand reaction patterns, students need mental access to a large amount of such information. Although this information could be looked up in reference manuals each time it was needed, the extra attentional demands would probably inhibit problem-solving ability (Schneider 1985).

The student works actively and independently with this program. It is the student's job to do everything from planning sequences of reactions and choosing a strategy for avoiding the beaker to guiding the flask around in the maze. When a student brings the flask up against an obstacle that reacts with the reagent in the flask, the obstacle disappears, with appropriate sound effects, and the score goes up by 10 points. If, however, the student attempts to destroy an obstacle that does not react with the reagent in the flask, the obstacle remains unchanged, the score decreases by a few points, and sound effects indicate that the flask has bumped into something solid. This procedure gives clear, immediate feedback and avoids extra attentional demands of verbal messages. (Occasionally, a reaction may produce an insoluble precipitate. In this case, the score increases, the initial obstacle is replaced by the precipitate, and the student must find a different reagent to remove it.) Because it uses a data base of chemical reactions and generates a new configuration for each game, CHEMAZE can provide the learner with a large number of problems.

The CHEMAZE display always shows clearly the player's progress toward the dual goal of removing obstacles from the maze and getting a high score. As reactions occur, obstacles disappear from the maze, and the score increases. The player has motivating knowledge of progress without additional demands on attention.

A Display Teaching Chemical Equation Balancing

Figure 8.5 shows part of a chemistry lesson that provides an automated display, akin to a spreadsheet, that helps students balance chemical equations (Smith, Chabay, and Kean 1983-85). The student's task is to "balance the equation" by inserting numbers in front of each chemical formula. These numbers must be chosen so that each type of atom is conserved in the reaction. For example, placing a 2 before HBr and a 3 before H_2O violates this constraint because then there are two H (hydrogen) atoms represented on the left and six on the right. The student moves the pointer (vertical arrow) to

Figure 8.5
Display from Balancing Chemical Equations

(Smith, Chabay, and Kean 1983-85)

3 right 6 to go

Use the keys: ← → 1 2 3 4 5 6 7
to balance this equation.

$$Fe_2O_3 + HBr \rightarrow FeBr_3 + H_2O$$

↑

Element	Reactants	Products
Fe	2	1
O	3	1
H	1	2
Br	1	3

the location of one of the coefficients in the equation and then types a number. The spreadsheet display is automatically updated to show the number of atoms of each kind on the reactant (left) and product (right) sides of the equation. It is therefore easy for the student to see when the equation is balanced or to diagnose exactly why it is not.

In this activity, the student works on the full task of interest, balancing chemical equations. The spreadsheet limits attentional demands and focuses the student on the central goal of equation balancing. This spreadsheet also provides instant specific feedback without adding to attentional demands. Although verbal feedback on errors is available, it is generally unnecessary because of the direct feedback on the spreadsheet.

Counters at the top of the screen mark the student's progress, displaying the tally of equations balanced correctly without help and the number remaining to be worked. Like CHEMAZE, this program can produce a large number of examples. The display is simple, uncluttered, and easy to understand. It contains essential information both for the task and for a sense of achievement, but nothing more.

A Tutorial on Word Problems

Figure 8.6 shows two screens from a program on word problems in chemistry (Smith, Chabay, and Kean 1983-85). Box A shows the problem statement and a student's first answer, with specific, immediate feedback on the probable nature of the error. The student has apparently neglected the fact that in the equation relating pressure, temperature, and volume, temperature must be expressed in degrees Kelvin (K), not degrees Celsius (C). Box B shows the same problem and answer, but this time it is the student's third, not first, error. After the second error, the program gives the original hint and shows the correct equation. After a third mistake, the program adds the answer and lets the student proceed. However, the student will again encounter similar problems later in the problem set.

Like the previous programs we have examined, this one embodies a detailed description of the processes the student needs to acquire. It is capable of generating solutions to show the student and of recognizing the mechanisms behind typical student errors. Again, the student works actively and independently on the full task of interest. Feedback is immediate and specific. Even better, by providing more general feedback at the first error, the student's opportunity to work relatively independently is preserved. However, if there is extensive misunderstanding, more help becomes available.

This program too is generative and can provide an essentially unlimited number of examples. The screens shown in Figure 8.6 come from the third part of a tutorial sequence. In the first part, the student is led step-by-step through similar problems, is prompted to identify variables and predict outcomes, is asked to set up equations without actually doing the arithmetic, and is finally asked to solve complete problems. In that initial part, limiting attentional demands to single steps takes priority over giving the student control over the entire task. A second part of the program provides an intermediate level of guidance, with the format enabling the student to work independently. The student controls the environment through a set of commands that call up a calculator, request help, or return the student to an index to choose another part of the activity.

Figure 8.6
Two Displays from Ideal Gases Showing Coaching on Word Problems

(Smith, Chabay, and Kean 1983-85)

Box A

A balloon filled with 2 L of gas at 21 °C is taken outside, where the temperature is -7 °C. What is its new volume?

> -.667 liter NO

You forgot to convert °C to °K.

Box B

A balloon filled with 2 L of gas at 21 °C is taken outside, where the temperature is -7 °C. What is its new volume?

> -.667 liter NO

You forgot to convert °C to °K.

$$V_2 = \frac{(2\ L)*((-7 + 273)\ °K)}{((21 + 273)\ °K)}$$

The answer is: 1.8 liters

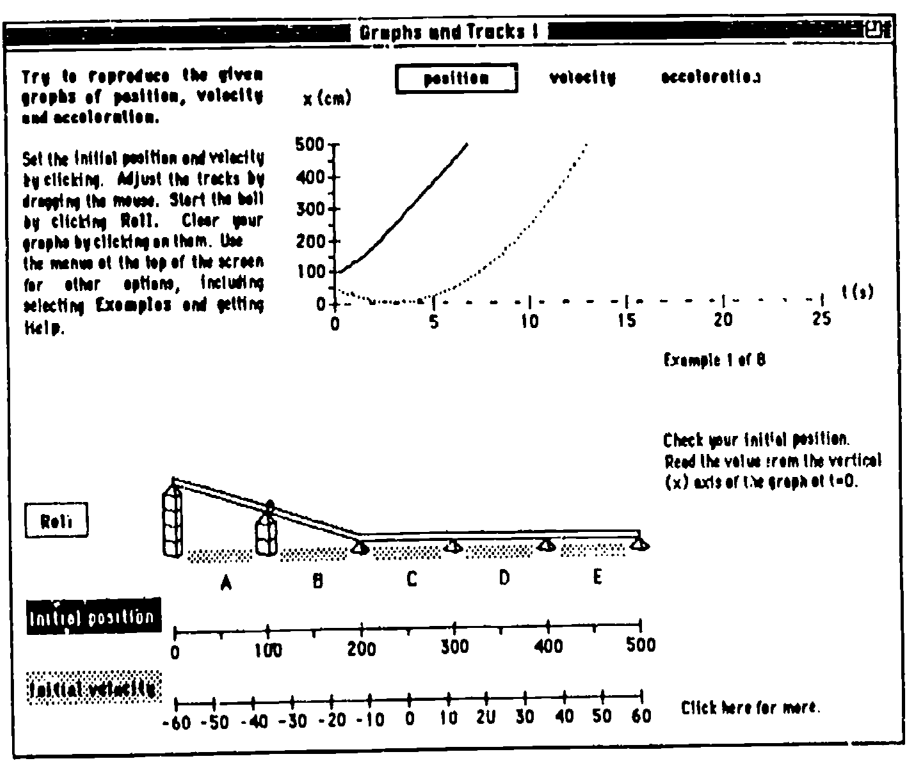
An Activity Relating Motion and Graphs of Motion

As mentioned earlier, scientists often redescribe problems using visual representations that draw on humans' powerful ability to make perceptual inferences. Perhaps the most common of these visual representations are graphs. Unfortunately, students have great difficulty relating graphs to the phenomena they represent. The program *Graphs and Tracks* (Trowbridge in press) attacks this difficulty.

Figure 8.7 shows a graph of the position of a rolling ball as a function of time. Below the graph is a simulated track supported by pillars whose heights can be adjusted by the student. There are also scales to allow the student to set the initial position and velocity of the ball on the track.

The student's task is to adjust the pillar heights and the initial position and velocity to make the ball's motion correspond to the motion represented by the graph. When the student clicks on the "roll" button, the ball rolls, and a graph of its motion appears, dashed to distinguish it from the original goal graph.

Figure 8.7
Display from Graphs and Tracks



Here again, the student has the opportunity to carry out the full task independently. Since inferring motion from a graph is a different skill from inferring a graph from motion, a second part of this program shows the motion of a rolling ball and gives the student the tools to construct a corresponding graph.

Feedback in this program is immediate and obvious: The graph of the rolling ball either does or does not match the target graph. Some students may have difficulty focusing on pertinent differences in the graphs. For example, a difference in the initial heights of the two graphs means that the ball has an incorrect initial position, but a difference in the initial slopes of the two graphs indicates an incorrect choice of initial velocity. Because focus of attention is an intrinsic problem for students in reading graphs, a request for help yields verbal comments on what changes might be useful. In Figure 5.7, the help statement suggests checking initial position and using the initial x value of the target graph. This program provides a large number of graphs for the student to work with and incorporates a facility for one student (or a teacher) to construct graphs for another student to solve.

Summary

All of these programs are winners of EDUCOM/NCRIPTAL software awards and have been shaped by extensive classroom use. They reflect many research-based criteria even though they were not necessarily designed to incorporate explicit models of the learning process. In the future, developers of instructional software may begin to build directly on these research results and incorporate into instructional software more explicit models of the learning process.

As we continue to study the use of interactive instructional software, we hope to be able to articulate more clearly some of the lessons, both cognitive and motivational, to be drawn from classroom experience with good science software. Research now in progress in areas such as how scientists understand and use diagrams and displays, and on how expert human tutors interact with students, will bring new insights to the design process as well. We can hope, in the next few years, to see increasingly interesting and effective computer activities for teaching physical science.

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9

A Perspective on Cognitive Research and Its Implications for Instruction

John D. Bransford and Nancy J. Vye

The contributors to this volume believe that cognitive research has important implications for instruction. Cognitive researchers study the mental processes underlying activities such as perceiving, thinking, and learning. By specifically studying the processes involved in reading, writing, mathematical and scientific thinking, and other activities, it should be possible to make significant improvements in instruction.

This chapter provides a perspective on this very active and important domain of research. The field is too large for us to do an exhaustive review; we focus on selected studies that are relevant to and expand upon the chapters in this book. (Other excellent overviews are provided by Pea and Soloway 1987, Resnick 1987, and Glaser and Bassok in press). We hope that readers will use our review

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and references to delve deeper into cognitive research that interests them.

Our discussion is organized around three areas of research that Glaser (1976) argues are necessary components of any adequate theory of instruction.

1. Research on the processes that underlie competent performance in any particular area. (What do effective readers do while reading? What do writers do while writing?)

2. Research on the initial state of learners before instruction. (What do they already know, feel, and believe about the area being taught.)

3. Research on the processes of transition from the learner's initial state to the final goal state. (What happens as learning occurs?) This category includes research on teachers' strategies and the social setting for instruction.

Studies of Competent Performance

We noted earlier that an important step in developing a theory of instruction is to study the processes that underlie successful performance in particular areas. This is quite different from an approach that focuses solely on the products that successful individuals produce. A simple illustration of the importance of studying processes is a study conducted by Ericsson, Chase, and Faloon (1980). They worked with a college student who spent over a year developing the skill of remembering number strings (e.g., 982761093). At the beginning of instruction, the student could remember strings of approximately seven numbers, which matches the estimates from Miller's (1956) research on constraints on short-term memory. At the end of instruction, the student could remember strings of over 70 numbers. Clearly, the practice paid off.

Imagine that you agree to help 30 students learn to remember number strings. Since your primary goal is instruction, it may not seem necessary to know anything about the processes an expert uses to remember number strings. Cognitive theorists argue that knowledge of those processes matters a great deal. One reason is that you need some idea of what you can tell students about what to expect from the instruction. At the end of the year, will they be able to remember other things, such as long letter strings (e.g., kcdsxmwpxioj)? A second reason for understanding processes is that you need to be prepared to help students who have difficulty. What if some fail to make significant progress despite practice? Do you conclude that they "lack the ability," or can you give specific instruction about strategies for learning? Knowledge of how Ericsson's college student did the task can be very helpful in this regard.

Ericsson and his colleague found that their student's improvement was not due to the fact that he "strengthened" or "enlarged" his overall short-term capacity. Instead, he learned to use specific knowledge to "chunk" information into meaningful groupings (Miller 1956). If you see the numbers 1-4-9-2, you can easily "chunk" them into a meaningful group labeled "when Columbus discovered America." Similarly, Ericsson's student had extensive knowledge about running, including winning times for famous races and the times for world and national records. With practice, the student learned to use his extensive knowledge of running to group numbers into meaningful chunks. Note that this strategy would not be expected to help remember strings of letters. Ericsson found that the yearlong practice with number strings did not help the college student learn to remember letter strings.

A number of researchers have studied experts to gain a better understanding of the cognitive processes involved in their performance (see Chi, Glaser, and Farr in press). Definitions of expertise vary in these studies; in some instances, the individuals studied are the best in their field in the world (e.g., grand masters in chess). In other cases, the "experts" are competent but not world-class. The important aspect of this literature is the contrast between those who do well versus those who do less well at various tasks. We focus on two types of studies that contrast the performance of experts with less-experienced individuals. The first explores the processes involved when experts are asked to solve a type of problem that occurs relatively frequently in their particular area. The second explores processes involved when people confront relatively novel situations and are asked to learn something new.

Problem Solving with Familiar Problem Types

A classic set of studies performed by the Dutch psychologist Adrian deGroot (1965) is an excellent illustration of ways to contrast the performance of experts with less-skilled individuals. DeGroot studied chess masters to understand the superior thinking and problem solving that enabled them to consistently win. In his studies, deGroot compared the performance of international masters with that of chess players who were extremely good but not ranked as masters. DeGroot focuses his research on the problem faced by chess players whenever they decide on a move. At each point in the game, they have to pick a move that will help them win. The choice of the best move involves complex decision making.

When deGroot began his research, he assumed that masters made better moves than less-skilled players (which they do, of course). Further, he assumed that masters were better because they could think of more possible moves than the other players and they could more accurately analyze the consequences of each potential move by thinking further ahead. DeGroot explored his hypotheses by presenting masters and less-skilled players with examples from chess games and asking them to choose the best move. He also asked the participants to think aloud as they considered various choices.

The results of deGroot's studies did not support his hypotheses. The masters' thinking was qualitatively, not quantitatively, superior. They did not think of more moves than did the less-experienced players. Nor did they choose a move and consider its implications for the next 20 moves or think of every possible move and systematically eliminate the poorer choices. Only relatively good possibilities seemed to come to mind.

One might be tempted to conclude that chess masters simply have a better "intuitive feel" for effective moves than do less-skilled players. This provides a label for a phenomenon, but it hardly helps clarify why the masters have "better intuitions." DeGroot believed that the chess masters must have developed a knowledge base that facilitated pattern recognition and allowed them to recognize the strengths and weaknesses of particular game positions. Based on this information, the experts were better able to generate qualitatively superior moves.

DeGroot attempted to test the idea that the masters' initial perceptions of chess game patterns were richer and more structured than the perceptions of less-skilled players. As one test of the pattern recognition hypothesis, deGroot showed masters and less-experienced players a chess game for five seconds and then asked them to reproduce the game (using new pieces and a new board) as accurately as they could. Results indicated that the experts were excellent at this short-term memory task, but less-skilled players had considerable difficulty. However, further studies by deGroot and by Chase and Simon (1973) demonstrated that the masters' excellent performance was not simply due to a superior short-term memory capacity. In the later experiments, chess masters were shown a game for five seconds and then asked to reproduce it from memory. On some trials, they were shown chess boards where the pieces had been placed randomly. In these instances, the chess masters were no better than less-proficient players at remembering which pieces went where. The masters' knowledge base consisted of meaningful patterns, and it did not help them encode randomly placed pieces. When the configurations were meaningful, masters could easily remember where nearly all of the chess pieces had been.

Comparisons of 10-Year-Olds and College Students

Experiments conducted by Chi (1978) compared the performance of young children (the average age was 10) and college students on several different tasks. One task involved short-term memory for number strings such as 2047938514. Not surprisingly, the college students performed better on this task. They remembered an average of eight numbers for each trial, whereas the younger students remembered only six. But when it came to chess, the results were the opposite. The young students recalled an average of over nine chess pieces arranged meaningfully on a chess board; the college students recalled about five and a half.

The youngsters who participated in Chi's study were avid chess players, but her college students did not play the game. By using chess pieces, Chi was able to assess any advantages the chess knowledge might provide—a lot, as the experiment showed. The data illustrate that "memory ability" is not some general propensity for storing information. Instead, our abilities to remember depend strongly on the nature of information we have previously acquired.

Pattern Recognition in Mathematics

Studies analogous to those by deGroot and Chase and Simon have been conducted in the area of mathematics (see Mayer 1985 for an overview). For example, Hinsley, Hayes, and Simon (1977) and Robinson and Hayes (1978) explored the cues experts need to identify particular types of problems. In these experiments, participants were read typical word problems a sentence at a time, and they quickly categorized them into various types. For example, if they heard, "A canoe travels 10 miles downstream," they would say, "That's a river current problem." Similarly, experts could readily decide which types of information were relevant for particular problem types. In simple river-current problems, for example, experts know that the weight of the boat rarely enters into the problem solution. But whether the boat is traveling upstream or downstream is extremely important, and so is the speed of the current. Experts are familiar with a number of basic problem types, and this rich knowledge plays an important role in guiding their strategies.

In a series of studies, Mayer (1982) focused on college students' knowledge of word problems in algebra. He estimated this knowledge by identifying different problem types and looking at typical algebra textbooks to determine how frequently these problem types appeared. In one study, Mayer asked students to read and then recall a series of word problems involving algebra. There was a strong relationship between accuracy of recall and how frequently the various problem types had appeared in texts. The students' rich knowledge for the higher frequency problem types apparently helped them remember relevant information. For the less frequent problem types, memory accuracy was relatively poor. These results are important because they suggest that expertise in mathematical areas involves more than general strategies such as "search for the relevant information and then calculate." Students' knowledge of particular problem types guides their strategies and helps them determine what is relevant.

Additional Studies of Expertise

In addition to the work in mathematics, the studies by deGroot (1965) and by Chase and Simon (1973) have encouraged researchers to study experts in many other areas. Examples include studies of expert versus novice computer programmers (Linn 1985), bridge players (Charness 1979, Engel and Bukstel 1978), radiologists (Lesgold 1988), physicists (Chi, Feltovich, and Glaser 1981), social scientists (Voss, Greene, Post, and Penner 1984), athletes (Allard and Burnett 1985), and teachers (Berliner 1986, Leinhardt and Greene 1986). In each case, experts have exhibited the kinds of pattern recognition abilities found in the research with chess masters. Expert programmers can quickly interpret and understand familiar computer programs; expert teachers can readily recognize classroom activities and group structures from a single, brief look at a picture of a classroom. Expert physicists can easily interpret and classify different types of physics problems.

Experts have also organized knowledge in different ways than novices. Chi and colleagues (1981) compared physics experts with college students majoring in physics. Both groups were presented with a set of physics problems and asked to put them into groups that belonged together. The college students tended to group problems in terms of specific, concrete features (e.g., problems involving an inclined plane, problems involving a spring). In contrast, the experts grouped problems according to abstract physics principles (e.g., "these all make major use of Newton's second law").

Researchers have also found that experts are better able to monitor their own thinking and problem solving than are less-experienced individuals. The experts can more accurately judge the difficulty of problems and hence apportion their time more effectively. In addition, they are better able to assess their progress and predict the outcomes of their performance (Simon and Simon 1979, Larkin, McDermott, Simon, and Simon 1980, Brown 1978, Chi, Glaser, and Rees 1982, Chi, Bassok, Lewis, Reimann, and Glaser 1988).

Different Approaches to Learning in Novel Situations

In the preceding studies, experts were asked to solve problems that were relatively familiar to them, but people also have to deal with novel situations. Hence, they need skills to learn new information. Researchers have explored differences in how successful and less-successful learners approach the problem of learning new information. As a simple illustration, imagine that your goals are to remember the following information about two robots and explain why each robot has particular features. Pay attention to what you do to achieve these goals.

> Bill's father worked for a company that made robots. His company made robots for a business that washed outside windows. They needed two kinds of robots. One kind of robot was needed to wash the outside windows in two-story houses. These windows were small. The other kind of robot was needed to wash the outside of windows of high-rise office buildings. These windows were big.
>
> Billy went to visit his father at work. He saw the new robots that his father had made. The robot used for houses was called an extendible robot. It could extend itself so it would be almost as tall as a two-story house. Billy saw that this robot had spikes instead of feet. It had legs that did not bend. Its stomach could extend in length to make it taller. The arms on the robot were short. Instead of hands, it had small sponges. In its head was a nozzle attached to a hose. Billy also saw that the extendible robot was made of heavy steel. It had an electric cord that could be plugged in. The robot also had a ladder on its back.
>
> Billy then saw another robot called a nonextendible robot. This robot could not extend in length. Billy saw that this robot had suction cups instead of feet, It had legs that could

bend. Its stomach was padded. The arms on the robot were long. Instead of hands, it had large sponges. In its head was a bucket. Billy also saw that the nonextendible robot was made of light aluminum. There was a battery inside the robot. The robot also had a parachute on its back.

Researchers at Vanderbilt used passages such as this with 5th graders and college students. The 5th graders included students whom teachers designated as academically successful or as less-successful learners. (Test scores corroborated with the teachers' ratings.) All students could decode written words, and even the less-successful students were fluent at reading the passage aloud before studying it for a test. Nevertheless, the academically less-successful students did very poorly at remembering which robot had particular properties and explaining why (Bransford, Stein, Vye, Franks, Auble, Mezynski, and Perfetto 1983, Franks, Vye, Auble, Mezynski, Perfetto, and Bransford 1983, Stein, Bransford, Franks, Owings, Vye, and McGraw 1983, Stein, Bransford, Franks, Vye, and Perfetto 1983).

Additional studies showed that the academically less-successful students failed to elaborate on what they were reading; they did not attempt to generate knowledge from memory that would help them understand why each robot had each property. College students and academically successful 5th graders spontaneously generated relevant elaborations. Here is one 5th grader's answer.

> You would know that the robot that had to go up on tall buildings to wash the windows would need to be lighter and not use an extension cord because it would be too long and might make it fall. It had a parachute in case it did fall. It also had large sponges because the windows were big. . . . You'd also know that the robot used to wash two-story houses was more heavy and had an extension cord 'cause there are plugs. It would rise up with its stomach and could spray with the hose that came through its head. You can't have a hose if you climb real high.

Several additional findings from the Vanderbilt study are noteworthy. First, when less-successful students were prompted to generate elaborations, they could do so. However, the information they generated was less relevant than the information generated by the more academically successful students. For example, given a statement like, "The robot had suction cups instead of feet," the less-successful students generated statements like "so it could walk" rather than "so they could stick to the building and climb." A second major finding from the Vanderbilt study was that the academically less-successful students seemed less able to monitor their own learning. (Recall in this connection the characteristics of self-regulated learners. See Palincsar and Brown, this volume.) They did not have a good idea about whether they had comprehended and mastered the information.

We noted earlier that the ability to monitor and regulate learning is extremely important. These abilities have been studied by researchers in the area of "metacognition." Brown (1978), Flavell (Flavell and Wellman 1977), and Markman (1979) were pioneers in this area; they studied people's abilities to monitor and regulate their own comprehension and learning. The monitoring portion of the Vanderbilt study reconfirmed their emphasis on the importance of metacognition (see also Belmont, Butterfield, and Borkowski 1978, Pressley and Levin 1983, Paris, Cross, and Lipson 1984, Paris, Newman, and McVey 1982).

This emphasis was also evident in a study by Chi and her colleagues (1988), who explored the learning strategies used by academically successful and less-successful college students as they encountered examples in their physics texts. The examples included information about how to solve particular problems, and the researchers wanted to find out how students would use these worked-out examples as they attempted to learn. Chi and her colleagues found that successful students engaged in a process of self-explanation; they tried to figure out why each particular aspect of the solution was applicable and asked themselves about other cases in which the general solution might also be applicable. As a result, they acquired an understanding that was more general than a memorization of the specific steps necessary for the particular problem in the text. Academically less-successful students showed much less of a tendency to attempt to explain to themselves why and when particular solutions worked.

Research by Dweck (1986) and her colleagues focuses on what people do when they encounter a difficult problem and fail on their initial attempts to solve it. Some people love the challenge; others attempt to get out of the situation and hence deprive themselves of the opportunity to learn. Dweck has been able to predict who will accept a challenge in the face of initial failure and who will give up. In general, students who think that traits like intelligence change with practice are much more likely to accept challenges and persist on tasks. Students who think that intelligence is fixed tend to do poorly after an initial failure. Dweck's observation of motivational differences between learners ties in with the cognitive and metacognitive differences, for in both cases better learners elaborate and go beyond the initial information.

Some General Findings from Studies of Competent Performance

In general, research comparing "experts" with less-successful or less-experienced individuals provides a number of ideas that are important for instruction. One way to use this research is to look for commonalities across all areas of expertise. A major common finding is that aspects of one's processing must become relatively automatic. Experts in a domain often encounter familiar problems. They are able to rely on automatized skills to recognize these problems. This fluent pattern recognition requires only a minimum of attention so the expert is free to deal with other aspects of the problem. In contrast, novices often feel overwhelmed because their lack of fluency or automaticity causes attentional strain (Schneider and Shiffrin 1977).

There are many processing bottlenecks that can overwhelm attention. In mathematics, these include a lack of fluency in basic mathematical computations (e.g., Bransford, Goin, Hasselbring, Kinzer, Sherwood, and Williams 1988) and in recognizing familiar types of problems (e.g., Mayer 1985). In reading, bottlenecks often involve a lack of fluency in recognizing individual syllables and words. In writing, it may be extremely trying for some students to spell correctly and to craft basic sentences; this may limit their abilities to keep track of their intended message. Overall, fluency in motor skills and pattern recognition skills seems important for effective performance in all domains. Of course, experts exhibit fluency that is backed by understanding. For example, their pattern recognition seems to be organized around meaningful principles that derive from core concepts in a field (e.g., Chi, Feltovich, and Glaser 1981). We say more about understanding in the discussion below.

Another reason to study competent performance is more domain specific. The studies help us identify key concepts and strategies that students must acquire to function effectively in a particular domain. In mathematics, for example, students must become familiar with certain kinds of problem types; in reading, they may need to learn about different story genres (e.g., Stein and Trabasso 1982). Anderson (1987) notes that general characteristics of problem solving differ across domains. For example, he argues that expert problem solving in physics involves a process of reasoning forward from a goal; the type of problem solving required in computer programming generally involves reasoning backward from a goal. To specify appropriate goal states for instruction, it is necessary to understand the problem-solving requirements of each domain.

In our discussion of experts, we noted that people are often asked to deal with novel rather than familiar situations. Under these conditions, our skills of learning and general attitudes about ourselves as learners become important. The ability to monitor and regulate learning activities is especially important for academic success (e.g., Brown, Bransford, Ferrara, and Campione 1983). Studies of the strategies and attitudes characteristic of successful and less-successful learners provide important guidelines for instruction. Instruction can be improved by focusing on these strategies and attitudes directly.

Assessing the Initial State of Learners

A second area that is important for understanding instruction involves research on the initial state of learners. Cognitive researchers have made considerable progress in this area in recent years. Let us return to the example of Ericsson and colleagues who worked with the college student learning to remember number strings. Assume that their instructional technique was to present practice problems (e.g., 04938217324) and give feedback about the correct answer. Should they package this set of techniques as a "successful curriculum"?

Ericsson's approach was successful given the student with whom he worked. However, the student began the instruction with well-developed knowledge that was relevant to the task (knowledge about runners and races), knowledge of how to use this information to "chunk" numbers, the belief that he was capable of learning, and the motivation to keep on trying. The "successful" curriculum that worked for this student may be much less effective for students with different initial states.

Children's Understandings of Balance Beams

Research conducted by Siegler (1985) provides an excellent illustration of the importance of assessing the initial states of learners. He studied the ability of children of different ages to understand the outcome of various experiments with a balance beam. For example, what will happen if a weight is put at the far end of one side of a balance beam (furthest from the fulcrum) and two weights are put on the other side near the fulcrum of the beam.

Through a series of careful analyses, Siegler was able to formulate the kinds of understandings that children of different ages had about the balance beam. He conceptualized these understandings in terms of rules. The simplest rule was "consider only the number of weights on each side of the fulcrum. If they are the same for each side, predict balance; otherwise, predict that the side with the greater weight will go down." A more complex rule was "consider both the weight and distance dimensions. Use the sum-of-the-cross products formula when one side has more weight and the other side has more distance." Instruction was most effective when it focused on the rule that was just slightly more complex than the one the child already held. Instruction several rules ahead had little effect.

Initial States With Respect to Math Facts

Research in the area of mathematics provides an additional illustration of the importance of assessing the initial states of learners. Consider the seemingly simple goal of helping students learn math facts like 4 + 7 = 11 and 2 + 5 = 7. At first glance, the only issue regarding the initial state of learners seems to be whether or not they know the answer to each fact. If they do, teach a different fact. If they don't, teach that fact.

But researchers such as Groen and Parkman (1972) have shown that there are many different ways to get answers to problems such as 4 + 7 = ?. Some children count on their fingers or count mentally. Others can simply retrieve the answers from memory. Among those who count, there are also important differences in strategy. Given the goal of adding 4 + 7, some students begin with 4 and count out 7 additional numbers. Other children use a shortcut strategy; they begin with the largest number (7) and count from there (8, 9, 10, 11). Interestingly, it appears that for many children this shortcut is invented rather than learned through explicit instruction (Groen and Resnick 1977).

As children get older, they proceed from simple counting to short-cut counting to direct retrieval of an answer from memory. However, research by Siegler (1986) shows that it is important to be more precise about assessment than is possible by looking only at general trends. He finds that for some sets of numbers (4 + 7, for example), a student may count on his fingers; for other sets (e.g., 5 + 5), the same student may retrieve information from memory. Different strategies are used depending on the specific knowledge of each number pattern that the student has acquired. (See Siegler 1986 for an analysis of the nature of the knowledge that guides children's selection of strategies.)

Research conducted by Hasselbring, Goin, and Bransford (1987) illustrates the importance of assessing the strategies used by each student for each set of numbers. They attempted to use computer programs to help math-delayed students learn to quickly retrieve number facts from memory rather than to count on their fingers. These middle school students were enrolled in special education and most continued to count on their fingers long after their peers had ceased using this strategy. Hasselbring and colleagues wanted to use drill-and-practice computer programs to help students automatize their math facts. This would free their attention to deal with more complex activities such as solving word problems and multi-digit addition problems (e.g., Resnick 1986).

In their initial assessments, Hasselbring and colleagues (1988) found that all students could retrieve some facts from memory (e.g., facts involving 1's and 2's and facts involving doubles such as 5 + 5). Drill and practice on these sets of facts helped children learn to answer much more rapidly. However, for those facts on which children used counting strategies, the drill and practice did not help them learn to retrieve from memory. It simply made them count on their fingers faster.

Based on this knowledge, Hasselbring and Goin (1985) developed a computer program that continually assesses whether students are using counting strategies for each set of number facts or are retrieving the facts from memory. Only when students can retrieve answers from memory are those facts entered into the drill-and-practice part of the program. The drill and practice facilitates faster retrieval from memory. For facts that still require counting strategies, Hasselbring and Goin designed a learning program that helps students move from a counting strategy to a retrieval strategy. When this is accomplished, those facts enter the drill-and-practice part of the program. As noted above, the purpose of this drill and practice is to make the retrieval more automatic so that attention is free to deal with other aspects of a task.

For our purpose, the important point of the Hasselbring and Goin program is that certain types of instructional conditions (e.g., drill and practice) are effective only given certain types of initial states of learning. If a student is still using counting strategies to answer 4 + 8, the data suggest that this is not the time to put that number pair into a set of drill-and-practice exercises. Instead, an initial learning phase is required so the student can learn to retrieve information from memory. Computers are especially well-suited for assessment and intervention activities such as this (see Larkin and Chabay this volume).

It is also important to note that Hasselbring and colleagues are not advocating that math facts be taught without developing an understanding of what one is doing. If the initial state of a learner includes no understanding of the fact that numbers are ordered (e.g., 8 is larger than 4), or no understanding of what is meant by addition, then memorization of number facts would be meaningless. The discussion by Kaplan and colleagues (this volume) provides important information about the kinds of intuitive knowledge that children bring to formal mathematics and the kinds of information that underlie a thorough understanding of number. The more we focus on understanding, the more important it becomes to assess the beliefs and strategies that students bring with them to the learning task.

Misconceptions

There are several ways to think about the initial state of learners. One is to ask whether the students lack the prerequisites for instruction. If the prerequisites are lacking, it seems obvious that they need to be supplied. A different way to think about the initial state of learners is to accept that students are not simply passive receivers waiting to be supplied with the correct information; they come to tasks with their own knowledge and expectations. Following Pea and Soloway (1987), we refer to these initial expectations as "preconceptions." Sometimes students' preconceptions are inaccurate, hence they represent misconceptions. The authors of this book (especially Minstrell) take very seriously the importance of assessing the preconceptions that students bring to instructional tasks (see also Anderson and Smith in press, Carey 1986, Feltovich, Spiro, and Coulson 1988, Wittrock 1986).

A study by Steffensen, Joag-Dev, and Anderson (1979) illustrates the importance of focusing on misconceptions. They asked college students to read passages about weddings. One passage, read by natives of the United States and natives of India, described an American wedding. The passage said that a bride wore "something old and something borrowed." U.S. natives interpreted this description as a positive situation; it involved a time-honored tradition. People from a different country interpreted it as a sad state of affairs. The Indian readers assumed that the couple must have had little money, otherwise they would not need to borrow things and wear old clothes. The Indian readers were able to comprehend the passage, but their interpretation involved a misconception due to the cultural knowledge they brought to the learning task. Note that the Indian readers thought that they were comprehending accurately. They did not experience a failure of comprehension such as most people feel when they try to understand a statement like, "The notes were sour because the seam split." (The clue "bagpipes" usually allows people to move from a state of comprehension failure to successful comprehension.) It is generally easier for readers to notice when they have failed to understand than to notice when they have misunderstood a writer's or speaker's intent.

The important point about misconceptions is that many approaches to instruction fail to correct them. It is not sufficient to simply present students with the "correct facts." One has to change the concepts or schemas that generate the students' inaccurate beliefs. (For a discussion of schemas, see Anderson 1984, Rumelhart 1980). Imagine working with the foreign students who had read the passage on American weddings. One way to correct their interpretation of the fact that the bride wore something old and something borrowed is to explain that she wanted to, but it seems clear that students' general schemas of American weddings would not be changed by this information. A better way to help the students might be to explain that the bride's choice represented an American tradition, but even this information is not sufficiently comprehensive. Meaningful instruction would help the students acquire an overall understanding of the traditions of American weddings and differentiate this newly acquired concept or schema from their concept of weddings in their country (see also Bransford 1984). Meaningful learning occurs at the level of concept acquisition and conceptual change.

Researchers in science education have conducted a great deal of work on misconceptions. For example, Anderson and Smith (in press) note that most 5th graders who are asked, "What is food for plants?" quite naturally assume that plant food is analogous to human food. They therefore list things like "rich soil," "water," and even "plant food that we can buy in stores." The photosynthesis process is very different from the idea of obtaining food for humans; plants get food only by making it themselves. If students are not helped to correct their initial misconceptions about this topic, they will not effectively understand.

Anderson and Smith (1984) also find that middle school children's conceptions of light and vision differ in important ways from scientific explanations. Students generally believe that their eyes work by seeing objects rather than by detecting reflected light. They believe that light shines on and illuminates objects, enabling the eye to see them. In addition, most students think that white light is clear or colorless rather than a combination of the colors of the spectrum. The concepts that generate these assumptions must be changed for effective learning to occur.

Minstrell (this volume) provides some excellent illustrations of students' misconceptions about physics. When thinking about the concept of "force," for example, students often assume that it is something exerted by active objects. In contrast, scientists understand that both active and passive objects can exert force. Kaplan and colleagues (this volume) discuss misconceptions in mathematics, noting that students can easily develop erroneous ideas that result in systematic errors. Palincsar and Brown and Beck (this volume) note the importance of misconceptions in reading.

Understanding Learning

So far, our discussion has focused on the importance of analyzing competent performance and assessing the initial state of learners. A third component of any theory of instruction involves assumptions about the transition from a student's initial state to some desired goal state (Glaser 1976).

A major assumption shared by a number of cognitive scientists is that new knowledge must be actively constructed by learners (e.g., Resnick 1987, Klopfer and Champagne in press, Klopfer, Champagne, and Gunstone 1985, Pea and Soloway 1987). One cannot simply "transmit" to students the secrets of expertise. This does not mean that information provided by teachers and texts is unimportant. However, it suggests that students must have the opportunity to actively use this information themselves and to experience its effects on their own performance. If they don't have the opportunity to use new information to achieve specific goals, students often learn facts that can be recalled only in specific contexts and otherwise remain "inert" (Whitehead 1929). The information is not used to solve new problems.

The Inert Knowledge Problem

The problem of inert knowledge can be clarified by returning to the passage about the climbing and extending robots. We noted that academically less-successful 5th graders did not spontaneously generate elaborations that helped them relate the structure of each robot to its function. However, with training on how to generate relevant elaborations, the students' comprehension and memory performance improved (see Franks et al. 1983).

Imagine that a group of academically less-successful students has been trained to elaborate when given a variety of different passages about robots. Imagine further that, one week after training, the students are given two passages. The one about deserts discusses facts about heat, lack of water, and sandstorms. A passage about camels includes facts such as "camels can close their nose passages," "camels have a great deal of hair around their ear openings," and "camels have special membranes to protect their eyes." Will the students who received elaboration training one week earlier spontaneously attempt to generate elaborations that help them understand how the features of the camels help them survive sandstorms and heat? A great deal of research suggests that, given many types of training, the answer is no (e.g., Bransford, Franks, Sherwood, and Vye in press, Brown et al. 1983, Pressley and Levin 1983). Students may be able to use elaboration strategies when explicitly prompted to do so, but, without prompting, their knowledge of strategies remains inert.

Bereiter (1984), illustrating failures to use important information, writes about a teacher of educational psychology who gave her students a long, difficult article and told them they had 10 minutes to learn as much as they could about it. Almost without exception, the students began with the first sentence of the article and read as far as they could until the time was up. Later, when discussing their strategies, the students acknowledged that they knew better than to simply begin reading. They had all had classes that taught them to skim for main ideas, consult section headings, and so forth, but they did not spontaneously use this knowledge when it would have helped.

Some Laboratory Experiments Relevant to Inert Knowledge

A number of investigators have begun to conduct studies of how people use knowledge, depending on differences in instruction. Studies by Asch (1969), Gick and Holyoak (1980), Hayes and Simon (1977), Perfetto, Bransford, and Franks (1983), Reed, Ernst, and Banerji (1974), and Weisberg, DiCamillo, and Phillips (1978) provide evidence that relevant knowledge often remains inert even though it is potentially useful. Gick and Holyoak (1980) presented college students with the following passage about a general and a fortress.

> 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 use it to solve the following problem.

> 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 the patient will die unless the tumor is destroyed. 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. However, the ray will also harm healthy tissue. 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?

When students were asked to use the information in the fortress problem to solve the ray problem, over 90 percent were successful. 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 cancerous tissue. However, the group in the Gick and Holyoak study that scored 90 percent on the ray problem had been explicitly told that information about the fortress was relevant to the tumor problem. In most problem-solving situations, we do not have the luxury of someone telling us which aspect of our knowledge is relevant. If we cannot access relevant knowledge spontaneously, it does us little good. That is why the most interesting part of the Gick and Holyoak study involved a group of college students who also memorized the fortress story and were then presented with the ray problem. Students in this group were not explicitly told to use the information about the fortress to solve the problem involving rays. For this group of students, the solution rate for the ray problem was only 20 percent.

The analogy between the fortress problem and the ray problem is not as direct as it could be. For example, the low-intensity rays are used to protect the healthy tissue. In contrast, the smaller groups of soldiers in the fortress problem are used to protect soldiers themselves rather than any innocent people (analogous to healthy tissue) in the enemy camp. Be use of the indirect analogy, the Gick and Holyoak study may overestimate the degree to which relevant knowledge remains inert. A study conducted by Perfetto, Bransford, and Franks (1983) was designed to explore issues of knowledge use with materials that were much more directly related to the problems to be solved. College students were asked to solve problems such as the following.

1. Uriah Fuller, the famous Israeli superpsychic, can tell you the score of any baseball game before the game starts. What is his secret?

2. A man living in a small town in the U.S. married 20 different women in the same town. All are still living, and he has never divorced any of them (nor have they divorced him). Yet, he has broken no law. Can you explain?

Most college students have difficulty answering these questions unless provided with hints or clues. Before solving the problems, some students were given clues that were obviously relevant to each problem's solution. For example, they were told, "Before it starts, the score of any game is 0 to 0; a minister may marry several people each week." Some students were then presented with the problems and explicitly prompted to use the clue information (which was now stored in memory) to solve them. Their problem-solving performance was excellent. Other students were first presented with the clues and then given the problems but they were not explicitly prompted to use the clues for problem solving. Their problem-solving performance was poor; in fact, it was no better than that of baseline students who never received any clues.

Perfetto's results represent an especially strong demonstration of failure to access knowledge because the clues were constructed to be obviously relevant to the problem solution. Indeed, the authors noted that before conducting the experiment they expected even the uninformed students to spontaneously access the correct answers because of the obvious relationship between the problems and the clues. It is important to note that by "access failure," Perfetto and colleagues are referring to students' failures to access the clue information while trying to solve the problems. The students accessed a great deal of other knowledge when trying to solve these problems. The activated preconceptions that most people have about these problems include assumptions that make it impossible to solve the problems (e.g., that the score being predicted was the final score of the game and that "marry" involved a groom rather than a minister). Perfetto's presentation of the original clue information did not change these assumptions, so the students' problem solving did not improve.

Overcoming the Inert Knowledge Problem

We noted earlier that research on cognition suggests that learning involves the active construction of knowledge. Teachers and texts can provide information that is useful for constructing new knowledge, but the mere memorization of this information does not constitute effective learning. Studies show that information that is merely memorized will remain inert even though it is relevant in new situations.

A useful way to think about meaningful learning is to view it as a transition from memory to action. Theorists such as Anderson (1982, 1987) argue that learning involves a transition from factual or declarative knowledge (e.g., knowledge supplied by a text or a teacher's instruction) to procedural or use-oriented knowledge. Put another way, Anderson's theory attempts to account for the transition from "knowing what" to "knowing how." Think back to the college student who learned to memorize lists that were 70 numbers long. At the beginning of instruction, this student had a great deal of factual, or declarative, knowledge about running times and races. The student had to learn to convert this declarative knowledge into procedures for encoding numbers into "chunks." This transition from "knowing what" to "knowing how" took a great deal of practice. Most instructors would like their students to learn how to read, write, and think like an expert scientist, mathematician, or social scientist. "Knowing how" appears to be an important goal.

Lesgold (1988) discusses differences between declarative and procedural knowledge. He asks his readers to imagine a teacher who has told students how to solve a particular type of problem and then assigns as homework a set of similar practice problems. The knowledge that is acquired from listening to the teacher and memorizing what he or she said is declarative knowledge. By itself, this knowledge does not help a student solve a homework problem. The student must be able to activate his or her memory of the teacher's comments at the right time and then interpret them—turn them into "mental acts" (p. 198). Lesgold's statement emphasizes the importance of learning when to use information. This is a component of "conditionalized" knowledge, which learning theorists who focus on the transition from declarative to procedural knowledge emphasize. As people transform declarative into procedural knowledge, they learn not only what is important but also when to do the right thing. If they don't know when to apply principles, concepts, and strategies, their knowledge remains inert (e.g., Anderson 1987, Larkin 1979, Newell and Simon 1972, Simon 1980).

Some Problems With Traditional Approaches to Instruction

Many traditional approaches to instruction do not help students make the transition from "knowing that" something is true to "knowing how" to think, learn, and solve problems. In 1929, Whitehead made the sobering claim that schools are especially good at producing inert knowledge. In 1940, Gragg made a similar claim and argued that we were failing to "prepare students for action." In his chapter on problem solving and education, Simon (1980) notes that many forms of instruction do not help students conditionalize their knowledge. He states that "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" (p. 29). It is left largely to students to acquire the information that will help them learn when to use various concepts, principles, and strategies. For example, students may learn the definition of statistical concepts such as "mean," "median," and "mode" and how to compute them. This knowledge is important, but does not guarantee that students will know when a particular statistic is the most appropriate one to use.

Franks, Bransford, Brailey, and Purden (in press) describe a textbook on experimental design and statistics for undergraduate students. One section, "Which test do I use?", begins: "How to choose a statistical test was postponed until now so that various aspects of data analysis could be presented." The author of the text then provided information about when to use various types of statistical tests. The entire discussion totaled 13 sentences. It is not difficult to predict students' performance given the small amount of practice they receive on when to use various tests. Generally, they are able to recall the steps necessary to obtain specific answers (e.g., they can calculate a mean, a correlation, a t-test). However, when students are asked to choose which tests to use in the context of analyzing an actual experiment, they have an extremely difficult time.

Concepts and strategies in subjects such as science must also be conditionalized; students must learn when to apply them. A number of investigators argue that the experience of merely reading new information in textbooks does not necessarily lead to effective learning because the new information does not replace previous misconceptions. When new situations are encountered, students' thinking is driven by their misconceptions rather than by the new information. Anderson and Smith (1984) illustrate how text-based approaches to instruction frequently fail to correct misconceptions. In one experiment they studied the effects of instruction designed to change middle school students' misconceptions of light and its effects on vision. In one condition of their study, students read a text for middle school students that used an analogy of a bouncing rubber ball to illustrate the general concept of reflection (light bounces off things like a rubber ball does). Students were later provided with problems such as, "When sunlight strikes a tree [a picture was provided to the students] it helps the boy to see the tree. How does it do this?" The results indicated that, for the vast majority of students (80 percent), the instruction did not correct their misconceptions. These students said nothing about reflected light.

A study conducted by Roth (1985) suggests why this might be so. She observed students and found that they used one of five different strategies or approaches to reading science textbooks, only one of which results in conceptual change. One strategy was to avoid thinking about the text while reading and then to rely on prior knowledge to complete activities related to the reading. A second strategy was to over-rely on words in the text to complete an activity. These students answered questions about their reading by matching key words in the questions with the same words in the text, and copying the sentences in which the matched words appeared. A third strategy was to memorize facts as they appeared in the text and try not to relate what was read to real-world knowledge. A fourth strategy was to rely too strongly on prior knowledge to make sense of the text. Because prior knowledge was strongly held and at the same time often in conflict with text content, students using this strategy had to distort or ignore some of the text information to make it fit. The fifth strategy was to change prior knowledge to make it conform with text content. Interestingly, Roth found that students using the fifth strategy—it was the one associated with the greatest conceptual change in students—were more likely to acknowledge feeling confused or having difficulty understanding the text, and they were quite often aware of the conflict between text content and their misconceptions. The Roth study highlights the fact that instruction must attend much more deliberately than it usually does to helping students learn when to apply their knowledge. In the next sections we consider some ways of doing this.

Learning by Doing

Many cognitive researchers argue that effective learning requires that we spend more time having students actively use knowledge to solve problems (this helps students "conditionalize" their knowledge) and spend less time simply reading about introductory facts and concepts. John Anderson and his colleagues at Carnegie Mellon University argue that, for many skills, the time spent reading introductory material and listening to teachers should be shortened and the time spent solving problems should be lengthened. Similarly, Anderson and Smith (in press) note that a series of carefully crafted problem-solving exercises was much more effective than text passages in correcting students' misconceptions about the nature of light. The authors in this volume appear to agree with the importance of helping students "learn by doing." They envision students who are actively engaged in activities such as reading for meaning, writing for a purpose, thinking mathematically, and explaining scientific phenomena. This is very different from spending most of one's time hearing or reading about strategies and concepts with little chance to use them to achieve meaningful goals.

It is important to note that cognitive psychologists' emphasis on learning by doing is not equivalent to the idea that teachers should merely hand out sets of practice problems and let students work on them. Simon (1980) notes that textbook authors and teachers often provide students with problem-solving exercises. Ideally, the problems should help students learn to recognize the general conditions to apply strategies and concepts. However, Simon also notes that the ability to conditionalize knowledge through practice depends on how one approaches the practice exercises. A difficulty with simply assigning practice problems is illustrated in the research by Chi and colleagues (1988), which shows that many students fail to use worked-out examples in texts to develop generalizable knowledge structures. A second difficulty is that students are frequently given practice on isolated components of skills and do not learn how to orchestrate these components to achieve broader goals. A third difficulty is that students often know the chapter the problems are coming from and use information about each chapter to guide their selection of strategies. When this chapter information is no longer available to them, they don't know what to do (e.g., Bransford 1979). Solitary practice provides no guarantee that students will learn effectively. If students persist in using the wrong strategies, solitary practice can even hurt (e.g., Anderson 1987, Perfetto, Yearwood, Franks, and Bransford 1987).

Solitary Practice versus Coached Practice

The authors in this volume assume students need the experience of "coached practice" (Lesgold 1988) rather than the more frequently encountered "solitary practice." The coach has a number of roles to fill and needs to assume different ones depending on instructional goals. The following characteristics of coached practice seem to be very important for helping students develop the expertise necessary to function effectively in various domains.

1. Coaches need to monitor and regulate students' attempts at problem solving so they don't go too far into the wrong solution yet have the opportunity to experience the complex processes and emotions of real problem solving. In intelligent tutoring systems, such as those developed by John Anderson and his colleagues, a computer coach intervenes relatively quickly to keep students from getting too far off track. In contrast, in instructional programs such as those described by Schoenfeld (1982, this volume), there appears to be more emphasis on letting students experience the processes involved in attempts to achieve mathematical insight before intervening too quickly. In mathematics as well as in other fields, attempts to solve novel problems often make people doubt their own ability. They feel they have reached a dead end. Experts in various areas know that problem solving often proceeds across days, weeks, and months, and that initial feelings of "it's impossible" often change as new approaches are discovered. However, it is not sufficient to simply tell this to students; they must experience it themselves. As Gragg (1940) states, "Wisdom can't be told." If students never get the chance to experience these processes, they can easily develop a misconception of the "one-minute problem solver"—either you get the answer to the problems very fast (e.g., you correctly remember the formula from the chapter) or you won't be able to solve the problem. Of course, it's not effective to simply let students continue to flounder indefinitely. In Schoenfeld's approach, for example, students are helped to reflect on their experiences and to see how various hints help them change the way they approach tasks.

2. Coaches help students reflect on the processes used while solving problems and contrast their approaches with those used by others. Sometimes this involves having students think aloud as they attempt to solve various problems (e.g., Bloom and Broder 1950, Whimbey and Lochhead 1980). At other times, students may attempt to solve problems and later discuss with one another different strategies they used. An important component of the attempts to help

students reflect on their own strategies is modeling. Students need to see how others approach various tasks. It is especially important that students see models of teachers and others who are working on novel problems. When the experts think aloud about these problems, they invariably reveal their own dead ends and stumblings rather than the "perfect reasoning" of the expert tackling a familiar problem. Basically, the teachers provide a model of "intelligent novices" (Bransford et al. 1988). Since the students are also novices, these types of models are relevant to them. Schoenfeld's approach to teaching mathematical thinking is an excellent illustration. He challenges students to present him with novel and difficult problems so that they can see his strategies as he thinks aloud. Models of teachers' attempts to understand difficult texts and plan for writing about new topics have been found to be useful as well (Bereiter and Scardamalia 1987, Palincsar and Brown this volume). Eventually, these models of thinking can be internalized by students.

3. Effective coaches use problem-solving exercises for assessment. By first letting students attempt to solve problems on their own—and to explain what they are doing and why—one has a much better chance to assess misconceptions. Minstrell (this volume) begins his science instruction with a phase designed to identify students' existing ideas (see also Anderson and Smith in press, Posner, Strike, Hewson, and Gertzog 1982). Larkin and Chabay argue that an important characteristic of good computer-based instruction is that it diagnoses and attempts to correct misconceptions and errors. The other authors also discuss the importance of designing instruction so that misconceptions can be identified.

4. Coaches use problem-solving exercises to create "teachable moments." They give students the opportunity to contrast their initial ideas and strategies with other possibilities. Posner and his colleagues suggest four characteristics of instruction that are necessary for conceptual change in the area of science instruction (Posner et al. 1982). We have changed the wording of these slightly to make them applicable to all academic areas. First, students must become dissatisfied with their existing conceptions; second, they must achieve at least a minimal understanding of an alternate way of conceptualizing the issue; third, the alternative view must appear plausible; fourth, students must see how the new conceptualization is useful for understanding a variety of situations. Posner's emphasis on the importance of experiencing the effects of new ways of thinking on one's own noticing and comprehension is, in our view, especially important (Bransford, Franks, Sherwood, and Vye in press). By seeing how new

knowledge effects their own perception and comprehension, students experience it as a tool for guiding thinking rather than as mere facts to be learned—facts that later remain inert. A number of laboratory studies suggest that when information is introduced in a problem-solving context, it is more likely to be used in new contexts rather than remain inert (e.g., Adams, Kasserman, Yearwood, Perfetto, Bransford, and Franks 1988, Lockhart, Lamon, and Gick 1988).

5. Coaches carefully choose problem-solving experiences that help students develop component skills in the context of attempting to achieve overall meaningful goals. In reading, for example, Palincsar and Brown do not use sets of unrelated exercises that provide decontextualized practice on specific strategies such as predicting and summarizing. Instead, students learn these strategies in the context of the overall goal of achieving meaningful comprehension—they therefore experience the effects of these strategies. In addition, instead of always asking students to answer questions generated by the teacher, Palincsar and Brown help students learn to generate their own meaningful questions. These generative skills are important for mature comprehension, but they often are not taught (e.g., Wittrock 1974).

Another illustration of designing meaningful problem-solving experiences is the types of exercises used by Minstrell and Schoenfeld. Minstrell creates problem-solving contexts that engage students' everyday knowledge and hence help them discover and correct their misconceptions. Schoenfeld creates problem-solving situations that help students experience the fact that their initial searches for solutions may come to dead ends and problems will momentarily seem impossible to solve. Other investigators use "microworlds" and videodisc-based "macrocontexts" to create problem-solving environments that invite problem finding as well as problem solving (e.g., Bransford, Sherwood, and Hasselbring 1988, Bransford, Sherwood, Hasselbring, Kinzer, and Williams in press, Collins in press). The choice of problem-solving exercises is very important. The tasks being designed by cognitive researchers are beginning to look quite different from the typical list of problems found at the end of chapters in texts or in workbooks. In addition, many hands-on activities in science classrooms lack the components of coached practice that we have discussed (Anderson and Smith in press).

6. Coaches do not necessarily have to be the classroom teachers or computer-based tutors. The authors recommend a classroom resource that is often underused—other students. By creating climates that foster cooperative learning, it becomes possible to help students

engage in active problem solving and reflection even though there is only one teacher and many students (see also Slavin 1987, Whimbey and Lochhead 1980). This emphasis on cooperative learning is also important for preparing students to deal with situations they will encounter frequently outside of school settings—situations that require group problem solving (e.g., Resnick 1986). As society increases in complexity, skills of cooperative learning and group problem solving may well become increasingly important for individual and national success.

Summary

Following Glaser (1976), we organized our discussion in this chapter around three areas of research that appear to be necessary components of any theory of instruction. The first component focused on attempts to understand the nature of "expert" or competent performance. Cognitive researchers have made important strides in this area. Each author in this volume makes assumptions about the nature of competent performance in his or her domain.

The second component of any theory of instruction involves research on the initial states of learners. Learners don't begin instruction as blank slates; instead, they approach new areas with a variety of preconceptions. When their preconceptions represent misconceptions, conceptual change must take place if meaningful learning is to occur. Often, the goal of instruction must be to change previously held misconceptions rather than to simply add new knowledge.

The third component of any theory of instruction involves assumptions about the nature of the transition from a student's initial state to various goal states—assumptions about the nature of learning. We noted that typical approaches to instruction often result in inert knowledge, and we discussed ways to overcome the inert knowledge problem. Our argument focused on the need to take seriously the goal of helping students transform declarative, factual knowledge into procedural, conditionalized knowledge. We cited many authors who argue that this is best accomplished by focusing on "learning by doing." We also noted that the current emphasis on learning by doing is quite different from an emphasis on merely providing practice exercises such as those that are found in workbooks.

The authors in this volume focus on "coached practice." Their goals for instruction are informed by the study of competent performance in their particular areas, and they take very seriously the need to assess and correct student misconceptions. They believe in the importance of "learning by doing" and they carefully orchestrate the activities of coaches plus attempt to create social climates that facilitate cooperative learning. Their ideas are provocative and stimulating. We hope that their chapters and our effort to place them in a larger perspective of cognitive research will serve as an in.itation to you to continue your exploration of contemporary research on students' learning.

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Toward the Thinking Curriculum: Concluding Remarks

Lauren B. Resnick and Leopold E. Klopfer

This yearbook lays the groundwork for an approach to curriculum and teaching that is based on recent conceptions of the nature of thinking and has been validated by cognitive research. Although a great deal of theoretical, experimental, and practical work remains to be done, we can now see real possibilities for creating a Thinking Curriculum that suffuses school programs. Those familiar with the constraints on American education, however, are likely to raise two important questions about the feasibility of adopting our authors' proposals, or others like them, on a wide scale. How can adequate time be found in the crowded school program for the kinds of educational activities advocated here? And how can the mandated testing and assessment that is demanded almost everywhere today be made compatible with the kind of education proposed by our authors? These are pressing questions that anyone who cares about educational reform in this country cannot afford to ignore.

The Problems of Time and Curriculum Coverage

Everything our authors propose for teaching takes a long time. They recognize that knowledge is acquired not from information communicated and memorized but from information that students elaborate, question, and use. All the processes involved in understanding a concept take a great deal of time. Real, usable knowledge cannot be constructed from brief exposures to information. Furthermore, problem solving, writing, or reading skills, as defined by our authors, are acquired through extended practice, not in short, discrete lessons. Single problems may take up whole class periods or longer; essays are revised and reworked many times; several hours may be spent interpreting just one story.

It seems clear that, if this is what the Thinking Curriculum requires, difficult choices will have to be made about what content to include. Textbooks will have to abandon their common practice of "covering" a great deal of material by treating it briefly with few connections among information.[1] But, in the face of many competing demands and interests, on what basis can we select a limited body of conceptual content for the curriculum? In the past, educators sometimes tried to solve the problem of content choice by avoiding it. They opted for a process emphasis for instruction, an approach that attempted to teach general skills of thinking and problem solving and gave little attention to teaching or structuring the content. However, mindful of all that has been said in this yearbook about the knowledge dependence of learning and the need for contextualized practice in using skills, we see that teaching appropriate content is crucial. Content-independent skill instruction does not solve the problem of content choice.

The solution seems to lie in teaching generative knowledge together with broadly enabling skills for learning. Generative knowledge can play a role in a large number of new learning situations. The authors have discussed a number of examples. These include the text structures, genres, and rhetorical conventions that can help students organize reading and writing activities. Fundamental concepts and principles in specific subjects can also generate future learning. In each discipline, certain key concepts organize and structure large amounts of specific information. In arithmetic, for example, a broad principle of decomposability of numbers underlies much of the elementary school curriculum. In history and government,

[1]A number of important studies document this tendency and analyze its effects. For example, Harriet Tyson-Bernstein (1988) describes the phenomenon for school textbooks in general. Isabel Beck, Margaret McKeown, and Erika Gromoll (in press) focus specifically on social studies textbooks.

recurring themes such as the nature of representative government or the roles of transportation and communication in national development could provide powerful boosts to much specific learning if they were well developed and understood by students. In economics, the concepts of markets and supply and demand organize enormous amounts of specific material. In biology, the broad principles of adaptation and the complementarity of structure and function are highly generative, as is the idea of molecular structure of matter in chemistry or conservation of energy in physics. A search for the generative ideas and concepts in each discipline could provide a principled basis for deciding among the many competing bits of knowledge that now fill textbooks and classrooms.

The kind of serious search for generative knowledge we are suggesting was strongly promoted in the 1960s by such visionary thinkers as Jerome Bruner and Joseph Schwab, who urged scholars and educators to identify the structure and essential concepts of all academic disciplines in school curriculums (Bruner 1961, Ford and Pungo 1964, Schwab 1964). Once identified, the disciplinary structures were to become the basis for building courses of study that would stress concepts in each school subject, not accumulations of poorly connected information. Active efforts to elucidate disciplinary structures and incorporate them into curriculums did not persist beyond the mid-70s, but a new effort to delineate the essential disciplinary knowledge for instruction in the natural sciences, technology, and mathematics has been undertaken by *Project 2061* at the American Association for the Advancement of Science (Rutherford 1989). Similar work is greatly needed for all disciplines.

Recognition of how generative knowledge organizes new learning is one of the justifications lying behind recent proposals for curricular reform based on elements of cultural literacy (e.g., Hirsch 1988). But the basis for choosing content in cultural literacy proposals is not usually its generative value; instead, content is chosen because it is (or should be, according to some,) knowledge commonly shared by literate persons in our society. Widely known content creates a basis for a common culture, which is a goal of the cultural literacy movement, but such content is not necessarily generative in new learning situations. In principle, it ought to be possible to identify key organizing concepts that are important aspects of cultural literacy *and* powerful generators of further learning. Such concepts and principles could well be chosen as the common core of knowledge around which the Thinking Curriculum is organized. It is important, though, not to imagine that just telling students about these key principles or concepts will turn them into usable, truly generative knowledge, even though students may become good at passing cultural literacy tests. To be generative, knowledge must become the object of thought and interpretation, called upon over and over again as a way to link, interpret, and explain new information that students encounter.

Testing as a Barrier to the Thinking Curriculum

Mandated testing imposed by states and local districts is a vast enterprise in the United States, touching the lives of students and teachers in virtually every classroom in the nation. In many states and communities, the tests are high-stakes affairs, whose outcomes affect not only prestige and recognition of educators, but also resources for instruction, the quality of teachers' work life, and even jobs. Under these conditions, it is impossible to consider important changes in the curriculum without taking into account the kinds of tests that will be used to assess students, teachers, and schools.

With only a few exceptions, the tests now in place were not designed to support the Thinking Curriculum. Most states draw heavily on a group of commercial standardized tests, or close imitations of them, that are tuned to an education in the basics that does not include thinking and reasoning. These tests, rooted in assumptions about the nature of knowledge that were brought to education by associationist and behaviorist psychologists, accord badly with the principles of learning and thinking put forward by cognitive researchers. The tests assume that knowledge is adequately defined as a collection of information that can be assembled in arbitrary ways. Therefore, collections of unconnected questions, rather than samples of extended problem-solving or reasoning activities, comprise the tests. The tests also assume that knowledge and skill can be lifted out of their contexts of use. This is why it was believed that writing skill, for example, could be adequately measured by sets of isolated questions on grammar, usage, spelling, and vocabulary.

Although these assumptions pervade almost all current standardized tests, the tests are not equally unfriendly to the principles of the Thinking Curriculum. Many reading comprehension tests, for example, display a degree of face validity. Students read passages and answer questions about those passages—surely one of the activities we expect people to do if they read with comprehension. We might wish for more extended passages, more complex interpretive questions, and, certainly, opportunities for students to formulate questions about what they read instead of just selecting answers to a test-maker's questions. Although we might hope to go well beyond what current reading tests ask students to do, at least some of the tests do not actively hinder efforts to move toward the Thinking Curriculum in reading. Indeed, Palincsar and Brown report that students in the programs recommended in their chapter score higher on tests like the widely used standard reading tests. The case appears to be otherwise in mathematics, however, where even the problem-solving sections of many standardized tests are limited to brief, relatively routine word problems with a single correct answer that students are expected to find quickly. Only in writing have significant advances been made. Several states, along with the National Assessment of Educational Progress and some college entrance exams, have introduced writing samples as part of their assessment packages. Students are given a topic on which they write an essay that is then graded by panels of judges whose procedures and ratings are carefully monitored and cross-checked to produce objective and reliable performance assessments.

Performance assessments of the kind now coming into widespread use for writing are needed for all school subjects if the Thinking Curriculum is to have a long-term chance to succeed.[2] The new writing-sample tests demonstrate that contextually valid performance measures are possible. Ways can be developed to keep cost down, largely by not testing all students every year. Educators interested in promoting thinking skills as a regular part of the school curriculum need to convince those in charge of testing in their states and school districts to introduce or extend performance assessments as a regular part of the mandated testing program. Even if the old tests remain, performance assessments that evaluate students' ability to engage in the kind of integrated, complex reasoning and problem solving that are the hallmark of the Thinking Curriculum will provide important public evidence of the kind of learning that can result. Eventually, performance assessments may become so accepted that it will be possible to eliminate the old collections-of-information tests altogether. When that occurs, testing practice will be fully consistent with the goals and operation of the Thinking Curriculum.

[2] The practical and technical matters associated with this kind of reform in accountability assessment are discussed in a paper by Resnick and Resnick (in press). For the science domain, the technical issues concerning assessment of students' reasoning and thinking skills are discussed by Klopfer (1971).

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