DOCUMENT RESUME

ED 361 395 TM 020 497

AUTHOR	Maloy, Kate
TITLE	Toward a New Science of Instruction.
INSTITUTION	National Research Center on Student Learning, Pittsburgh, PA.
SPONS AGENCY	Office of Educational Research and Improvement (ED), Washington, DC. Office of Research.
REPORT NO	ISBN-0-16-041885-2; OR-93-3232
PUB DATE	Aug 93
CONTRACT	G008690005
NOTE	77p.
AVAILABLE FROM	U.S. Government Printing Office, Superintendent of Documents, Mail Stop: SSOP, Washington, DC 20402-9328 (Stock No. 065-000-00589-1).
PUB TYPE	Reports - Evaluative/Feasibility (142)
EDRS PRICE	MF01/PC04 Plus Postage.
DESCRIPTORS	Agency Role; Conflict; *Constructivism (Learning); Educational Practices; *Educational Research; Elementary Secondary Education; Federal Government; Inferences; *Instructional Effectiveness; *Learning; Mathematical Concepts; Models; Reading Comprehension; Science Education; *Teaching Methods; *Theory Practice Relationship
IDENTIFIERS	*National Research Center on Student Learning

ABSTRACT

Research conducted by the National Research Center on Student Learning (NRCSL) is reviewed as it moves toward a new understanding of learning and instruction. Research by the NRCSL into the kind of learning demanded by modern life has been shaped by the understanding, based on earlier research, that knowledge is actively constructed in the mind of the learner, and not just accumulated and stored for use. To engage in the construction of knowledge, learners must eventually attain intellectual independence. A fundamental concern of research at the NRCSL has been the relationship between knowledge and skill in effective learning. The focused and mindful drawing and testing of inferences appear to be powerful skills that may be indispensable to a strong conceptual understanding in school subject matters. This implication is found in the following areas of NRCSL research: (1) building on intuitive understanding of numbers and quantities; (2) linking background knowledge to new knowledge in text comprehension; (3) learning from effective learners in science; and (4) learning about the value of cognitive conflict. Research on teaching is indicating the importance of modeling by the teacher of mindfulness in learning. The outcomes of NRCSL research have the potential to enrich both research and practice, and the success of every school child depends on investigations such as these. (SLD)

Toward a New Science of Instruction

OFFICE of RESEARCH
U.S. Department of Education
Office of Educational Research and Improvement

Toward a New Science of Instruction

By
Kate Maloy

U.S. Department of Education
Richard W. Riley
Secretary

Office of Educational Research and Improvement
Sharon P. Robinson
Assistant Secretary

Office of Research
Joseph Conaty
Acting Director

This document was prepared with the help and cooperation of the research staff and administration at the National Research Center on Student Learning. The author wishes to acknowledge and thank her colleagues for their generous support.

August 1993

This report was prepared by the National Research Center on Student Learning with support from the Office of Research, Office of Educational Research and Improvement, U.S. Department of Education (Grant No. G008690005). The report does not necessarily reflect the position or policies of the Department.

Copies of this report are available from the U.S. Government Printing Office. For further information, call their Order Desk at 202–783–3238. The GPO stock number for this book is 065–000–00589–1.

For sale by the U.S. Government Printing Office
Superintendent of Documents, Mail Stop: SSOP, Washington, DC 20402-9328
ISBN 0-16-041885-2

Foreword

The Office of Research in the U.S. Department of Education supports research to improve education policy and practice. The goal of our work is to illuminate those educational problems and issues that are of greatest concern to the American people. This is accomplished through basic and applied research carried out by universities, school districts, teachers, and individuals across the nation.

One of the most important areas we have funded in recent years is the intersection between sound basic research and the actual practices of classroom teachers. The cognitive processes involved in teaching and learning have shown this intersection to be critically important. As researchers have developed new conceptions of how students learn, teachers teach, and schools operate, the involvement of teachers and schools in many of the research projects has greatly enriched the findings and made them more applicable in the classroom.

A leader in this field is the National Research Center on Student Learning (NRCSL) at the University of Pittsburgh. Researchers there have been examining how students "learn to think and think to learn." With funding from the Office of Research and its predecessor agency, the National Institute of Education, NRCSL has explored many facets of knowledge construction, including how students can develop thinking and reasoning skills that allow them to generate deep comprehension even from incomplete information. Educators now understand the importance of inferences—both making them and testing them—as students create deep understanding of content material.

This book describes projects undertaken at NRCSL from 1985 to 1990 that examine reasoning and learning processes in mathematics, science, social science, and the comprehension of texts. As this book clearly demonstrates, education research is a rich and varied enterprise with great power to benefit and learn from education practice.

Joseph Conaty
Acting Director
Office of Research

Contents

Executive Summary

The National Research Center on Student Learning (NRCSL) pursues a new vision of education, one in which every American student gains both abundant knowledge and the ability to apply it. To meet the challenges of an increasingly complex world and workplace, students must become what NRCSL Director Robert Glaser calls "mindful architects of their own knowledge"—thinkers who know a great deal and continually adapt, refine, and use their knowledge. The basic skills of an earlier time—a fundamental competency in reading, arithmetic, and the tasks of citizenship—are no longer enough by themselves. Success today requires new basics: the ability to reason, analyze, plan, and act effectively in a climate of pervasive change.

Students must become "mindful architects of their own knowledge."

NRCSL's research into the kind of learning demanded by modern life has been shaped by the understanding, based on earlier theoretical studies, that knowledge is actively constructed in the mind of the learner, not just accumulated and stored for use. The construction process requires the learner to link incoming information with existing knowledge and make sure the connections are sound. This means adjusting for contradictions and making appropriate, reasoned use of the understanding that develops. The process never ends. Each new situation in which understanding is applied generates further information and insights, and these in turn may call for subtle or radical reconfigurations of the learner's knowledge structures. Such knowledge structures are thus fluid and constantly changing.

In order to engage in such fluid knowledge "architecture," learners must eventually attain intellectual independence. Once they have become full-fledged workers, citizens, and consumers, most will have little access to direct instruction. So if instruction must eventually turn learning over to the learners, education research must investigate how it can do so.

Thinking and Reasoning

Projects at NRCSL have approached this question from many directions. Some have examined the cognitive and social processes of instruction to see how different components of schooling affect the development of reasoning skills. Others have compared good and poor learning strategies, explored how the rules of a discipline affect the way a learner thinks about its content, or assessed the role of existing knowledge in the acquisition of new knowledge.

But a fundamental concern of all NRCSL research is the relationship between knowledge and skill in effective learning. It is impossible either to reason without some piece of knowledge to reason about or to acquire that

Learners must become aware of what they do not know and be able to bridge the gaps in their knowledge.

piece of knowledge without using some skill in reasoning. As NRCSL Director Lauren Resnick has said, students must learn to think and think to learn. They must learn to read but also learn to question, probe, and reason about the content of texts. They must learn to calculate but also understand which calculations to use when, and why. They must learn about scientific phenomena not only from texts and lectures but also by posing hypotheses, designing experimentation strategies, and analyzing the results of their experiments. In all cases, learners must become aware of what they do not know and be able to bridge the gaps in their knowledge.

In this sense, knowledge construction—the bridging of knowledge gaps—requires learners to reason with incomplete information. They must begin with what they already know, target what they want to learn, and think their way to truly "educated" guesses as to the skills and information that will connect the two. For example, a reader who opens a history text will already know something about the period it covers, if only the names of a few prominent figures or events from that time. But unless the text is truly well matched to the student's level of background knowledge—an infrequent case—the student will constantly have to monitor and adjust her comprehension. She must identify the points at which her understanding breaks down and figure out how to compensate for holes in both the text and her own knowledge.

Such inferential processes are central to deep learning, regardless of whether a student is questioning the validity of an author's message, broadening her intuitive, preschool knowledge of numbers and quantities to encompass early formal mathematics, or trying to explain an unfamiliar scientific phenomenon in terms of concepts she already grasps.

Sophisticated learning skills like these are important for all American students. The deep understanding that arises from a balanced interplay between thinking and learning, skill and knowledge, is valuable for its own sake but also empowers and motivates learners. Students who see beyond facts and procedures to the principles that bring them to life are likely to regard themselves as effective thinkers, people who can generate sound solutions to unexpected problems. Students who gain such confidence are the ones who indeed become the mindful architects that Robert Glaser describes. Reforms that can support such learning are needed everywhere, because most American classrooms still rely too heavily on rote or didactic methods that do little to promote true reasoning and problem solving.

Lessons About Learning: What Research Can Offer Instruction

When research at NRCSL first began under OERI funding in 1985, investigators were beginning to ask how the idea of knowledge construction, as opposed to passive absorption of knowledge, might be applied to instruction and disseminated to schools. Research in the center's first 5 years both supported theories of knowledge construction—in mathematics, science, social science, and text comprehension—and illuminated the construction process. Studies of cognitive processes by which learners build their knowledge suggest that learning and deep understanding depend on the ability to reason well with incomplete information—which means tuning in to existing knowledge, recognizing gaps and points of breakdown in comprehension, and constructing solid connections across those gaps. Thus, the focused, mindful drawing and testing of inferences appears to be a powerful skill, one that may be indispensable to a strong conceptual understanding in school subject matters. This implication runs clearly through each of the areas of research discussed below.

Students who see beyond facts and procedures to the principles that bring them to life are likely to regard themselves as effective thinkers, people who can generate sound solutions to unexpected problems.

Math Learning: Building on Children's Intuitive Understanding of Numbers and Quantities. A consistent characteristic of the knowledge children gain about numbers before they enter school is that their understanding requires no justification or explanation. Children do not need to ask whether, or why, drinking from a glass of juice leaves less juice in the glass. Experience tells them this is so, just as it tells them that cutting a pie into eight wedges does not change the total amount of pie in the pan. Children gain this kind of understanding from daily, real-life encounters with large and small objects and quantities and from observing and comparing them under many different circumstances.

A strand of analytic research at NRCSL examined children's pre-school grasp of fundamental math concepts and suggested that bringing preschoolers' practical, hands-on experience with objects and quantities into the classroom could ease their transition to formal mathematics learning. It was thought that encouraging primary-grade students to invent and discuss their own solutions to mathematical puzzles could lead them to discover for themselves many concepts and procedures standardly taught in the early mathematics curriculum. This theory has been supported in a collaboration between the researchers who helped to generate it and an elementary mathematics teacher who joined with them in hopes of improving her young students' arithmetic skills and comprehension. Over the past 6 years, this teacher, in consultation with the research team, has introduced, refined, and closely evaluated a variety of new teaching techniques, all designed to encourage children's discovery of arithmetic concepts and computations. Each year, standardized test scores have testified to steady improvements in these children's understanding of arithmetic and to their growing confidence in their ability to reason mathematically. The knowledge they have gained through experimentation, discussion, and group problem solving appears to be as clear and self-evident to them as children's pre-school understanding of quantities. The children in the reformed math classes are able to justify and explain their solutions to problems and describe their pathways to those solutions.

A challenge for research is to identify scientifically sound ways that instruction can make complex learning tasks more accessible.

This kind of learning, which shows an awareness of principles as well as methods, is deeper than that which is gained by learning facts and mechanical procedures alone. Nevertheless, one NRCSL study comparing the cognitive complexity of two different methods of subtraction suggests that, at least in some cases, it is easier for students to learn procedures than to grasp the underlying concepts and principles. Since learning with a deep understanding of concepts is richer and more useful over a lifetime than procedural learning alone, a challenge for research is to identify scientifically sound ways that instruction can make complex learning tasks more accessible.

Further evidence of the greater power of conceptual learning comes from another collaboration between research and practice. This project has introduced techniques that, like those described earlier, are based on guided student inquiry and discovery rather than on direct teaching. The reforms in this case were developed and broadly disseminated through teacher training materials written and produced by members of the American Federation of Teachers. The materials were based on these experienced teachers' clinical expertise combined with their understanding of math education research at NRCSL and elsewhere. The union of the two forms of understanding gave rise to the new instructional materials, which have succeeded with both students and teachers. One teacher, for example, said that her goal was no longer just to teach basic skills but to use them to help her students become good thinkers and problem solvers. As she put new forms of instruction to use, she saw children who had never spoken in class begin to contribute, and she saw students devising a variety of valid solutions to problems. Their confidence and enthusiasm reached gratifying new levels.

The success of these two collaborations in mathematics education can be explained in part by other work at NRCSL that has continued to analyze children's acquisition of number sense and mathematical concepts. This work theorizes that children develop a rich cognitive understanding of quantities, numbers, and mathematical operations in a particular order; that all the levels of understanding they acquire can be useful at any time; but that the order in which they develop should not be ignored or violated by instruction. This notion of children's progression from intuitive understanding to an ability to grasp formal concepts is embodied in the new approaches to instruction that the two collaborative projects have developed.

Text Comprehension: Linking Background Knowledge to New Knowledge. NRCSL studies of text comprehension have identified a range of inferential processes, from relatively low-level abilities to highly sophisticated skills. In one study, for example, findings showed that basic reading skill, regardless of subject matter, requires the reader to infer numerous small pieces of information, such as the antecedent for a pronoun or the implicit object of an action. Such inferences are essential in all reading. They have more to do with text syntax and structure than with conceptual content, and they bridge very small knowledge gaps, sometimes without the reader's conscious effort.

When the knowledge gaps are larger—as when a history text mistakenly assumes young readers already understand a concept such as taxation without representation—a more focused and mindful use of inference can help to bridge those gaps. This possibility is illuminated in another text-comprehension project that closely analyzed both the content and intent of elementary school history texts in order to identify exactly where and why these texts presented problems for young readers. Researchers revised the problematic texts to compensate for the identified weaknesses and then gave groups of students either the original text or the revised text, alone or with supplementary background material. Students who read the revised version alone learned and understood the text's content better than students who read the original text with or without the background information. But students who read both the revised text and the background material performed the best of all, supporting the notion that coherent texts are most powerful when students have sufficient knowledge to reason well about their content.

Science Learning: Lessons From Effective Learners. The mathematics and text-comprehension research strongly implies that instruction can guide and discipline students' intuitive tendency to infer what they are not directly told by texts or teachers. The implication is further supported by research on science learning that compares the learning strategies of better and poorer learners in several settings.

The first of these science learning projects is connected to work on text comprehension because it examines the understanding that students gain from reading science texts. Students in this project were asked to read a problematic text on the human circulatory system and to assess their understanding of each sentence as it was read. Researchers supplied high-level prompts as the students read, asking them questions designed to stimulate a deeper probing of the content. A striking outcome was the finding that several of the more effective learners accurately inferred facts and concepts that the text covered poorly or not at all. Their means of doing so resembled the skills involved in the text revision processes described above, but these effective learners were not reading in order to improve the text or to generate explanations for classmates; they were compensating for text inadequacies even as they read, continually generating explanations that would fill gaps in the material presented.

Readers' responses to researchers' prompts suggested that significant textual inadequacies—large gaps that required a major piece of information to be added, such as the function of a circulatory system component—could sometimes be overcome by a gradual process in which numerous minute inferences were drawn from practical experience, common sense, background information on the subject, or earlier passages in the text. The cumulative effect of these seemingly insignificant inferences eventually supported the larger inference—the generation of the missing piece of information needed to bridge the comprehension gap.

This process of slowly amassing inferences often required learners to correct for errors along the way. An incorrect inference would come to light when the reader encountered contradictions in the text or when one inference failed to mesh satisfactorily with others. To address such cognitive conflicts, readers had to generate and test new inferences until the contradictions were resolved.

Self-explanation and cognitive conflict together make a powerful learning technique.

Self-explanation and cognitive conflict together make a powerful learning technique. The first, if viewed as an ability to be cultivated through careful instruction, provides the means of resolving the second. Although the good readers in the science text study were better able than poorer ones to take advantage of researchers' searching prompts, the work on self-explanation suggests that most students could be taught to ask themselves these kinds of questions. This could foster habits of thought through which readers would constantly evaluate written material for its completeness, clarity, consistency, and accuracy. These are the kinds of skills that motivate students, raise their confidence, and lead them eventually to intellectual independence from formal instruction.

Variations on the skills of self-explanation were investigated in another study of effective science lean ng, one that focused on scientific experimentation as a means of constructing new knowledge and linking it to existing knowledge. This research is especially informative about the inferential nature of deep learning because it not only compares good and poor strategies but also compares structures of learning in three science topics—microeconomics, electrical circuits, and the refraction of light. Students were asked to devise and carry out experiments in each topic as a means of discovering the topic's governing rules and principles. A computer microworld in each topic offered an environment for simulated, hands-on experimentation, and an intelligent on-line tutor helped students evaluate their experimentation strategies throughout.

Different strategies were effective in different topics, depending on such factors as the relationships among variables or the reliability of students' existing background knowledge. All students conducted experiments in all three microworlds, working in the refraction microworld last because successful discovery in that topic required a combination of the skills and techniques needed in the other two topics. Students' experimental and inferential skills improved steadily as they progressed through the three microworlds, suggesting that the skills they developed in the first two were helping them with their discovery processes in the third. In addition, the most successful students adapted their skills appropriately for different knowledge domains.

Researchers attributed this result to students' "learning how to learn." The students who learned the most about successful scientific discovery engaged in different kinds of experimenting activities than the students who learned less. For example, when effective learners searched for evidence of a microworld's governing principles, they typically arrived at tentative hypotheses after only one or two experiments and then attempted to confirm those hypotheses in a systematic way. Poorer learners did not distinguish between data that could suggest and data that could test hypotheses. Similarly, successful learners quickly recognized and responded appropriately to experimental outcomes that contradicted their hypotheses, whereas those who were less successful tended to misread or misinterpret such feedback and to persist in unproductive experiments.

These comparisons support the notion that focused, mindful inference-making processes tend to generate systematic, efficient learning activities that in turn foster a deep understanding of a topic. Like the research on mathematics learning and text comprehension, this work further implies that the knowledge gained from discovery activities and the deliberate use of inferential skills is authoritative, useful knowledge. Because it is imbued with both content and skill it is more likely to be useful in unfamiliar situations than knowledge comprised of facts and mechanical procedures alone.

Learning About Argumentation: The Value of Cognitive Conflict. At the heart of every discipline are strict standards for measuring the soundness of evidence concerning the discipline's principles, facts, and conclusions. In disciplines such as social science the defense of arguments and assertions often rests on informal reasoning as well as on empirical evidence. Because successful knowledge construction so often involves generating and testing arguments and claims, new learners need to grasp and observe the rules for doing so.

All students argue, but very few learn how to argue clearly and effectively.

NRCSL research on argumentation demonstrates the value of deliberate instruction in the structure and evaluation of arguments. All students argue—just as all students draw inferences—but very few learn how to argue clearly and effectively. NRCSL research found that typical texts and classrooms do not offer many opportunities for students to practice or analyze argumentation skills—any more than they offer practice in text analysis, mathematical discovery and invention, or intensive experimentation. History texts that were examined, for example, did not analyze events and their causes but merely stated the facts of historical matters. It is not surprising, then, that student attempts to explore and defend their ideas are haphazard rather than carefully reasoned. By the end of middle school, this research indicated, few students are able to identify or evaluate the components of arguments—premises, examples, counterexamples, conclusions—and fewer still can construct an argument-based paragraph. Thus, they lack a form of reasoning that is essential to conceptual understanding in many subject matters, and they are unlikely to reach intellectual independence without this skill.

Although argumentation need not involve conflict, NRCSL research suggests that defending an opinion against opposing viewpoints in small-group discussion may promote learning. Instruction might capitalize on this possibility both by teaching the principles and standards of informal argument and by designing group interactions for practical experience in argument construction and justification.

Small-group research at NRCSL investigated different effects of cognitive conflict in minority- and majority-opinion holders and studied the degree to which the need to argue a minority or majority viewpoint stimulated study and research on the issue, the students' own position, and the opposing position. Findings indicated that just the anticipation of having to defend an opinion in front of others who may disagree strongly motivated students to learn and think about the topic being debated. The research also suggested that differences in the groups' minority/majority ratios and in the amount of confidence and background knowledge the arguers possessed could determine whether—and which—group members were likely to be swayed by the arguments of others.

Together, the strands of research on the learning that can arise from skill in argumentation and informal reasoning provide good evidence that practice in argument generation, analysis, and justification can make deliberate a process that everyone uses naturally but not always to greatest effect. Designing situations in which learners encounter and must respond to interpersonal cognitive conflict can provide settings for such practice.

Lessons About Teaching: Modeling Mindfulness

If instruction must eventually turn learning over to the learner by imparting intellectual strength and adaptability, the people who design and carry out instruction must both have and model those same qualities. Teaching, like learning, is often a matter of working with incomplete information. So teachers, like their students, must be able to hazard inferences that can close knowledge gaps. Unlike their students, however, teachers must guide and assess both their own and others' skill and comprehension.

For example, explanations at the heart of much instruction are inherently incomplete, just as texts and arguments are, and it falls to the teacher to provide sufficient detail and definition for her students' level of background knowledge. She may test for background knowledge at the beginning of instruction, but day to day she will have to monitor student comprehension, identify problem areas, and adjust her teaching to compensate. At the same time, her construction of explanations and her ability to guide classroom discourse require reasoning skills that she can model for her students even as she assesses and attempts to nurture their reasoning abilities.

These and countless other complex tasks are demanded by the need for higher educational performance in this country. But teachers cannot excel at such tasks unless they themselves are skilled at self-explaining, compensating for their own knowledge gaps, assessing their classroom performance, and perceiving and adjusting for weaknesses in their own and their students' arguments. Many teachers who wish to improve their instruction therefore find it necessary to pursue higher professional standards than they have been trained to achieve. It stands to reason that, if too many American schools are still bound to educational goals that stress the rote mastery of so-called basic skills, too few teachers have been encouraged and offered the opportunity to instill in their students the guided and fully intentional use of the inferential skills necessary for accurate knowledge construction and solid conceptual understanding. If teachers want their students to become mindful architects of their own knowledge, then the teachers themselves need to be mindful architects, too—not only of their own knowledge but of the fluid and complex teacher-student relationship called instruction. The teachers who participated in the mathematics collaborations at NRCSL, for example, all found the pursuit of higher professional standards integral to their goal of raising standards for their students.

If teachers want their students to become mindful architects of their own knowledge, then the teachers themselves need to be mindful architects.

Some of the groundwork for the NRCSL collaborations and for the recognition that teacher professionalism is crucial to successful education reform was laid by analytic research at NRCSL on the complex cognitive processes involved in expert instruction. This theoretical work helped to raise the research community's awareness of how intricate the processes of teaching are—how many considerations a teacher must juggle at one time, how subtly cues from students may signal comprehension difficulties, how expertise builds over years of practice. This research identified and described in detail many components of successful lessons and instructional techniques, often in the context of contrasting the methods of inexperienced teachers with the methods of experts.

However, researchers alone—even those who have conducted extensive classroom-based studies—do not continually experience the real-world difficulties and dilemmas of introducing reforms into an environment that may resist, obstruct, or merely fail to understand important departures from longstanding norms. Only teachers, once they have grasped research findings that support sound instructional innovations, can adapt those findings and innovations to the needs and realities of their classrooms, schools, students, and colleagues. Teachers who wish to promote the widespread, research-based reforms that American education urgently needs must not only achieve new levels of professionalism but must also train and mentor their colleagues.

The relationship between NRCSL research and classroom practice has been part of a research cycle in which theoretical investigations may eventually move into the development and refinement of new instructional methods, often through close collaboration with teachers. These efforts may well lead in turn to fully applied work in which the innovations are demonstrated in pilot classrooms and then disseminated to additional schools and school districts. Finally, these classroom applications may raise new questions for theoretical research. For example, a line of mathematics research at NRCSL that has been applied in classrooms for more than 3 years has now generated new work, a qualitative analysis of these classrooms that attempts to understand theoretically why the applications succeed.

In addition to the ongoing mathematics applications, research on science learning plans to study and develop instructional interventions in consultation with participating classroom teachers. The text processing project now works directly with students and with teachers, instructing them in text revision processes and studying the effects those processes have on learning and understanding. Finally, the work on informal reasoning and argumentation has moved beyond the basic investigations described above and now aims to develop and test instructional techniques for motivating and imparting the skills needed to construct and justify sound arguments. As these applications proceed, they too may confront new theoretical questions—questions that would never emerge at all if not for the intersection of research with classroom practice.

Beyond the Outcomes

Every outcome of NRCSL work at every stage of the research cycle has the potential to enrich both research and practice. No single finding or application is discrete. When theory suggests an innovative classroom tool or technique, the outcomes may improve instruction, confirm or refute aspects of theory, and generate further insights for continued investigation.

We know from theoretical work that active reasoning is crucial to a grasp of concepts and principles; and we know from many of the classroom interventions being developed, tested, and disseminated through NRCSL that instruction can indeed impart to students the critical, self-regulatory habits of mind that support conceptual understanding. But much remains to be accomplished, both at NRCSL and in the field as a whole. We need to learn more about *why* and *how* certain circumstances, tools, and techniques enhance the learning process. We need to understand more about each complex component of effective teaching, from explanations to the monitoring of students' comprehension. We need to see more clearly into the cognitive processes that support conceptual understanding so that we can continue to develop instructional methods that reflect and work with the mind's own activities. The success of every school child in the United States depends upon investigations such as these.

Introduction

A Persistent Double Standard in Education

A century ago, in the newly industrializing United States economy, mass education evolved largely to serve the needs of mass production. Most workers were expected to perform isolated tasks within the production process, executing procedures rather than planning or evaluating them, and carrying out assignments rather than asking questions or offering ideas. It was therefore assumed that the majority of children, who would enter work of this nature, needed no more from their education than fundamental competency in reading and computation. Both job knowledge and the knowledge learned in school were conceived as sets of basic skills, applied to the job at hand with no necessary grasp of the larger purposes being served.

These larger purposes—the complex responsibilities of business, government, higher education, and the professions—were seen as the proper concerns of a small minority. As a result, a few students were held to higher expectations than the rest. They were encouraged to reach energetically for what today are called "higher-order" skills, which enable students to question and investigate assertions, devise and test hypotheses, analyze and solve problems, and apply knowledge beyond school boundaries. Education of this quality had been around for centuries, but it was reserved for those who would one day manage or govern.

These two standards of education—one for the majority and one for the elite—reflected the prevailing view that learning was a stepwise process, with sophisticated "thought" taking place only at the pinnacle. Learners were thought to acquire knowledge from the ground up, mastering elementary concepts and procedures before tackling complex problems. Moreover, it was thought that fundamental skills were best achieved through repetitive drill and practice and that factual content was best absorbed directly from declarative lectures or texts. "True" reasoning—the ability to interpret, assess, adapt and apply knowledge—was somehow activated only after enough basics were in place. Only a few students needed to proceed that far.

The double standard in American education may have evolved generations ago, but it persists today in the large gap between the quality of instruction received by students from privileged backgrounds and by children from economically disadvantaged communities. Though the distribution of the higher and lower standards may be somewhat different today than it was earlier in the century, those standards still fall on opposite sides of an economic dividing line. Today, however, that line frequently coincides with a racial or ethnic division, and another dividing line can often be perceived between boys and girls.

The Need for a Single Standard

Though it has long been clear to many scientists and educators that the hierarchic view of learning and the double education standard are outdated, replacing them is now urgent in this country. Rapid changes on several fronts—economic, demographic, and political—call for new forms of instruction that can raise all students to higher levels of thought and performance.

Rapid changes call for new forms of instruction that can raise all students to higher levels of thought and performance.

In the first place, the United States economy no longer relies so heavily on the manufacture of goods. Instead, the business of the country centers increasingly on an array of new commodities and services: information, communications, marketing, consulting, electronics. Where manufacturing continues to take place, its operations are being streamlined, with fewer workers taking more responsibility. Instead of working on fixed tasks in isolation from coworkers, employees are being asked by more and more companies to work in teams, set goals, meet budgets, solve on-the-job problems as they arise, and monitor productivity and resources. Moreover, research has begun to illuminate many complex forms of reasoning that underlie the performance of on-the-job work. These findings belie the notion that jobs can be performed unthinkingly and suggest that that idea has fostered too bleak a picture of human competence. As the workplace continues to change, workers will increasingly be expected to solve novel problems, to plan and communicate effectively, both orally and in writing, and to reason in a way that once was considered possible only at the peak of a long educational climb.

Second, as most Americans know, the transition to an altered economy coincides with extraordinary demographic changes. Growing segments of our population come from other parts of the world or from subcultures within our own country. Rising numbers of households are headed by women. More and more children are falling below the poverty line. As the standards of the workplace change, those entering the job market are increasingly women and/or members of racial or ethnic minorities. Unless long-standing patterns change, many who are most in need of better education will be the least likely to receive it.

Finally, the exercise of conscientious citizenship is becoming more demanding. Knowledge is expanding, and information is flowing at unprecedented rates. All Americans, native-born or immigrant, English-speaking or not, need to be able to understand and think critically about an intricate web of social and global concerns. What are the ethical implications of new technologies in medicine, biogenetics, artificial intelligence? Is it possible to repair environmental damage and still meet the needs of a growing world population? What are the potential hazards or benefits of economic protectionism? What are the comparative merits of plans to reduce the national budget deficit or to establish national health insurance? Voters will need to grasp such issues in order to be counted as members of an educated citizenry.

Newer Views of Learning

The growing complexity of the workplace and the world in general mean not only that we must enable all students to think and reason well but also that the tools and techniques applied to that goal must be sound. Fortunately, as the need for education reform and for a single education standard has evolved, a corresponding evolution has taken place in the science of human cognition. In recent decades, studies have shown that true learning is never passive or straightforward but richly active and complex. As NRCSL Director Lauren Resnick writes in the monograph *Education and Learning to Think*, the complexity of learning at all levels is "the most important single message of modern research." The "higher-order" skills of reasoning and problem solving are not the outcome of advanced education; they are integral to successful learning at every level, even the most elementary. "In fact," writes Resnick,

> the term "higher-order" skills is probably itself fundamentally misleading, for it suggests that another set of skills, presumably called "lower order," need to come first. This assumption—that there is a sequence from lower level activities that do not require much independent thinking or judgment to higher level ones that do—colors much educational theory and practice. Implicitly at least, it justifies long years of drill on the "basics" before thinking and problem solving are demanded. Cognitive research on the nature of basic skills such as reading and mathematics provides a fundamental challenge to this assumption.

The challenge to which Resnick refers arises not only from evidence that intricate thought processes are involved even in simple addition and the fundamentals of reading but also from scientific findings about the nature of learning itself. Studies of human performance—in problem solving, expert instruction, text comprehension, the conduct of experiments, and the construction of arguments and explanations—all support the view that learning is a lifelong process in which new knowledge must continually be meshed with existing knowledge in the learner's mind. This process is greatly affected by the accuracy and coherence of new and existing knowledge and by every aspect of the setting in which learning and instruction take place, from the human interactions to the use of language and the management of time and materials.

Understanding is best attained by treating knowledge as if it were a living ecosystem rather than a static artifact.

People who learn and perform well are able not only to construct accurate mental representations of knowledge but to adapt and reconfigure these constructions in response to new information. They constantly assess their comprehension, connect new information with concepts they already have, repair mismatches between existing and new knowledge, identify barriers to further understanding, resolve ambiguities, and so on. The relation between knowledge and the mind of the learner can no longer be viewed as the relation between contents and container. Understanding is more organic than manufactured, and it is best attained by treating knowledge as if it were a living ecosystem rather than a static artifact.

The Proper Aim of Instruction: "Mindful Architects" of Knowledge

In a paper entitled "The Maturing of the Relationship Between the Science of Learning and Cognition and Educational Practice," NRCSL Director Robert Glaser recalls that "philosophers from Plato to Erasmus" regarded education as consisting not so much of instruction as of "study"—study being equated with reasoning and inquiry. Instruction played a subordinate role because it was meant to render itself unnecessary. Its purpose, Glaser says, was to turn students into "mindful architects of their own knowledge," master builders who could engage in constructive thought and exploration based upon their experiences. This did not mean that instruction was not of the utmost importance, but that it was an indispensable means toward an end that would supersede it.

But the double education standard in this country permitted an emphasis on instruction almost as an end in itself. It was possible to meet the need for a literate but not truly "mindful" workforce through drill, practice, memorization, and lecture, all of which worked best when students were passive and unquestioning. In a sense, cognitive science has rediscovered and elaborated what the ancient philosophers knew. By investigating the active, probing nature of true learning, research has reinforced the centuries-old idea that the point of education is not simply to deliver knowledge and pass along mechanical skills but to kindle in students an inquiring disposition and to engage them in developing the independent means of satisfying curiosity. From this revitalized perspective, research can now ask what instruction of this kind should look like today. As Glaser observes, findings from cognitive science's early focus on human performance—that is, on the outcomes of learning—are now able to support "an overlapping later phase [of research] in which learning processes are more central . . . . This phase is characterized by the analysis, design, and evaluation of conditions for learning in the light of modern knowledge of cognition."

A New Intersection of Research and Practice

As research moves more deeply into the study of educational means as well as outcomes, it naturally comes into more direct and sustained contact with the world of practice—a world in which school systems and classroom educators are under increasing pressure from politics and the public to produce sweeping, measurable improvements. That pressure is only compounded by the lack of consensus about the shape these improvements should take and the means for accomplishing them. Some people urge a return to basic skills, despite evidence that the basics will never again suffice. Others want to see "critical thinking" being taught directly. Still others focus on raising students' SAT scores, or reducing dropout rates, or minimizing drugs and violence in schools and on playgrounds.

In the face of such pressure, and amid the argumentative clamor for reform, it is easy for teachers to feel beset rather than supported. Many may dismiss research as irrelevant to an overload of daily responsibilities carried out with little opportunity even to talk with other teachers. Others may be intrigued by scientific findings but discouraged from further investigation by bureaucratic obstacles and requirements. Still others may be unaware that substantive research on classroom issues is even being conducted.

The fact remains, however, that even the most persuasive and applicable findings of science will languish unless teachers can put them into practice. Thus, if one challenge to cognitive science is to test and refine its findings until they can support truly effective reforms, another, inseparable challenge is to understand the texture and the daily tensions of a teacher's life. Research cannot begin to recommend or design realistic new strategies for instruction without being deeply familiar with the world in which reforms must take hold.

Similarly, classroom educators cannot permanently or effectively ease the pressure for change unless they absorb some scientific principles upon which to refine or reform their teaching. Once they have some knowledge about the world of research and the kinds of questions cognitive science asks and investigates, teachers can more confidently choose among the many prescriptions being offered for education's ills.

When experts from the two educational fronts—practice and research—are able to engage in genuine, sustained collaborations, they usually find that their joint concerns and methods produce outcomes that neither could have accomplished without the other. The territory in which they share their knowledge, work out their differences, and develop a common language has been labeled a "third space" by some researchers at NRCSL. It is a crucial space, and one that grows with each collaborative effort.

What comes out of this third space, however, depends on what is put into it. Researchers and practitioners alike must come to their collaborations with a deep understanding of their own world and of the problems they must address together. Important collaborations in mathematics learning and instruction have been launched through NRCSL, and their success has depended largely on analytic studies conducted at the center. These studies, and others, are discussed in this report together with descriptions of NRCSL's collaborative projects in mathematics.

Thinking Through Mathematics

Concerns of Research: Connections Between Learning and Understanding in Arithmetic

Mathematics as a discipline encompasses many forms of reasoning. Interpreting a word problem, judging the best way to express it in formal mathematical notation, performing the necessary steps in calculation, and then assessing the appropriateness of the answer to the situation in the problem—all these involve somewhat different problem-solving skills. The learning of mathematics, then, has great potential to foster the higher-order thinking skills that are increasingly demanded of instruction. But if mathematics is taught only as a series of mechanical procedures, and not as a rich field of inquiry, instruction will usually yield—at best—speed and accuracy of calculation but little grasp of underlying principles. Generations of children in the United States have begun their mathematics studies in strictly traditional classrooms that use just this approach. Today, many students are still taught that there is only one correct way to perform each basic arithmetic operation, and they are required to work quietly, by themselves, on repetitive drills designed to indelibly imprint correct procedures.

Although cognitive research has yielded much evidence that a different approach—one which allows children to experiment, discuss, and question—is more effective, some children in traditional settings have nevertheless done very well, even going on to excel as mathematics researchers or teachers. Far too many other children have done poorly, however. They have never understood the motivating principles that lie beneath their calculations, have never seen a connection between math and their lives outside the classroom, have never appreciated the patterns and symmetries of numerical relationships.

With the problem-solving and reasoning skills that math can instill becoming more important, and with test scores of U.S. students lagging far behind those of children in other countries, it has become a pressing concern of education research to discover why arithmetic is so difficult for so many children and what can be done about that difficulty. As one researcher at NRCSL has pointed out, early math is no harder than mastering many video games, yet too many students who excel with a joystick in their hands go blank when it is replaced by a pencil or a piece of chalk in math class.

It is important that the effort to replace the blankness with enthusiasm and comprehension be a balanced one. The fact that some children learn well in some traditional settings has led to strands of research at NRCSL that ask just what it is that works in these settings—as well as what can go wrong. Other research projects investigate promising, newer approaches to mathematics instruction, emphasizing full comprehension of both principles and procedures in arithmetic. But whether researchers focus on refining or on substantially replacing traditional methods of instruction, their projects all ask: "How should arithmetic be taught?" And in this sense they all challenge, inform, and stimulate each other. In addition, they all investigate, to varying degrees and from divergent perspectives, most of the major influences on knowledge acquisition and construction that have been identified by cognitive research. These influences include, as we have noted earlier, the nature and role of existing knowledge, the coherence of learners' mental representations of knowledge, students' and teachers' metacognitive processes (which help them to diagnose and repair learning difficulties), and the many features of the settings in which learning takes place.

What Makes Counting Easy, Subtraction Hard?

One tightly focused project at NRCSL—an investigation into the cognitive complexity of two subtraction algorithms—began with questions about concepts of counting and other basic processes. But the work also serves larger questions: Why do children learn counting so easily and yet find arithmetic so hard? What is the connection between the concepts involved in a math problem and the procedures used to solve it? How are the rules for performing arithmetic procedures constructed in the learner's mind?

The project's principal investigator, Stellan Ohlsson, has centered his exploration on the "HS" system, a sort of "electronic learner" that he designed in order to "teach" it the concepts of counting and arithmetic. HS would then perform calculations based on its understanding of these lessons, and Ohlsson could observe the system's errors, self-correcting procedures, and resulting efficiency and accuracy. HS thus simulated the cognitive learning and rule-building processes of actual learners, providing what Ohlsson calls, "a model that starts with knowledge of the concepts and principles and learns how to do arithmetic tasks correctly."

Ohlsson's first sessions with HS were on counting, which he says is "the simplest of all arithmetic procedures—one that children learn quite well, unlike the arithmetic in school." He found a direct connection between the skill of counting and the principles of counting, a perfect overlay of a conceptual template upon a procedural activity. "Learning to count," Ohlsson says, "has all the nice properties you would want school instruction in arithmetic to have. For instance, children can, if you change the counting task on them in some unusual way, readily adapt to this. They don't fall apart. So, you ask a child to count the pens here on my desk, and he does so and tells you there are nine. You can then say, count them again and make sure the red one is number three—and the child will be able to adapt his counting to that constraint."

Such flexibility apparently comes straight out of the direct, *inflexible* connection between the principle and the skill of counting. "The source of children's success with counting," Ohlsson says, "is that the idea constrains the behavior." In fact, the idea virtually is the behavior. "The concept of one-to-one mapping that underlies counting is reflected in the performance," Ohlsson continues. "Every step in counting is dictated by the principles, so if you do any step but the right one, you will be violating the one-to-one mapping." To learn counting, then, is to learn the principle, even though a child enumerating the pens on Ohlsson's desk might not be able to say why he does it the way he does.

Subtraction is a different story. In order to investigate the connection between the principles and the procedures in one topic of subtraction, Ohlsson taught HS how to subtract using two different procedures, or algorithms, and he taught each algorithm both conceptually and mechanically. The question was, which algorithm, taught by which method, could HS learn and perform better?

The algorithms taught to HS were *regrouping* and *augmenting*. Either can be used to solve what is called a *non-canonical* subtraction problem; that is, one like 42 minus 19, in which a digit in the *subtrahend* (19) is larger than the corresponding digit in the *minuend* (42). Regrouping, familiar to Americans, involves "borrowing" from the position immediately to the left of the too-small number in the minuend. In the example here, this would regroup the components of the minuend, 42, from 40 + 2 to 30 + 12. The 9 in 19 could then be subtracted from 12 instead of from 2. Augmenting, taught in Europe, simply adds equally to the minuend and the subtrahend. Thus, 42 and 19 might each be increased by 5 (or by any number from 1 through 8 that would rephrase the problem as a canonical one—such as 47 minus 24—without changing its outcome).

A comparison of the effectiveness of the four lessons not only moved toward settling an old dispute in early math education but also suggested a hypothesis for why arithmetic is so difficult for children to learn. Close observation of the steps, errors, corrections, and rule refinements that HS went through revealed that augmenting, taught mechanically, was most easily learned; regrouping, taught conceptually, was hardest to master. This ran counter to traditional wisdom in the field, which had held that regrouping was cognitively simpler to learn. The significant difference, Ohlsson found, lay neither in the concepts nor in the algorithm itself, but in the "attention allocation" of the electronic learner HS. "What we observed while running the model is that there are more complicated attention allocations in regrouping; in other words, the eyes move about over the display in a much more complicated pattern—and, of course, knowing the mathematical principles of subtraction isn't going to help with attention allocation."

Regrouping and augmenting are not the only two algorithms that one can use to perform mathematically correct subtraction. And there are many algorithms for many other kinds of arithmetic problems. Once a learner confronts a situation in which the behavior is not entirely constrained by principles, as it is in counting, then, says Ohlsson, "choosing the best algorithm is guided by expediency considerations." Thus, the conclusion he has drawn from running HS is that "even if you understand the underlying concepts and principles, there is still the problem of deciding what to do. You can't derive the most efficient algorithm from the mathematics, because the mathematics doesn't talk about that. We now think that is why it is so hard to learn subtraction, or other math, in a conceptual fashion. We think that is why so many instructional interventions fail, because they go in and try to teach the concept of place value, for example, and then find that the students still don't perform the calculations any better."

Because Ohlsson is concerned with efficiency in instruction, he questions whether time and effort involved in teaching arithmetic conceptually are well spent; yet he also concedes that "when you teach mechanically, that tends to rob the child of his own authority over the correct procedures." This matter of "authority," considered in the light of other work at NRCSL, may be what fills the gap between concepts and procedures in arithmetic.

What Do Children Know About Numbers? What Do They Need To Be Taught?

Intuitive knowledge has an authority all its own.

Research on mathematical intuitions—that is, a grasp of basic numerical properties and relationships that children develop without formal instruction—indicates that such intuitive knowledge has an authority all its own. For example, preschool children know the difference between larger and smaller objects or amounts. They know that drinking milk from a glass reduces the amount inside the glass and that pouring milk into the glass increases its contents. They know that a quantity remains constant if nothing is added or subtracted. They know that if an object is cut into pieces, the pieces taken together contain the same amount of material as the uncut object. And most of them know both how to count and how to use counting to quantify sets of objects. Children regard such knowledge as self-evident. This is an important characteristic of intuitive knowledge: It requires no analysis or justification.

What preschool children do not know, and what formal instruction has traditionally been assigned to teach them, are the rules, symbols, and language of mathematics and how to use them in calculations. And it is in the course of formal schooling that children too often begin to lose their sense of authority and confidence about mathematical thinking—though they may not realize that is what they engaged in before entering the classroom.

NRCSL work on the intuitive knowledge of young children, led by Lauren Resnick, has thus investigated the gap between conceptual and procedural understanding from a different perspective than Ohlsson's. In this case, the gap exists between mathematical intuitions that develop easily and almost universally and the difficulties that arise in the learning of formal mathematical notations and procedures in school. Like Ohlsson's work, Resnick's research asks why arithmetic is so hard; but it also asks why, if children enter school with strong and accurate intuitions about basic mathematical relationships, those intuitions do not help them to learn school math.

Resnick hypothesizes that the classroom emphasis on manipulating formal symbols discourages children from applying—or trusting—their informally developed understanding. She further suggests that the reason for the discontinuity is that children's intuitions arise directly from their real-world experiences, whereas formal instruction in math requires them to reason about abstractions such as numbers and operators that they cannot experience directly. Support for these hypotheses is provided by some of the "buggy algorithms" that young learners use in attempts to solve arithmetic problems—systematic routines that look right in terms of procedural rules but that fail to connect the manipulation of symbols with what the symbols represent.

A common "bug" analyzed by Resnick is called "borrow-from-zero." When a student tries to solve a non-canonical subtraction problem using the regrouping method,

$$\begin{array}{r} 6\;\not{0}^{9}\;2 \\ -\underline{4\;3\;7} \\ 2\;6\;5 \end{array}$$

the bug appears in the middle column. The student writes 9 correctly but fails to continue borrowing from the next column to the left. This procedure obeys rules of calculation (e.g., in borrowing one must cross out and rewrite the numeral to the left of the column that is incremented), but it fails to conserve the total quantity in the minuend. Thus, the mechanical operations appear to break down at the point where their connection to the meaning of the problem

It is in the course of formal schooling that children too often begin to lose their sense of authority and confidence about mathematical thinking.

is lost—an error that reflects the gap between intuitive and formal processes of learning.

In addressing the question of how to close the gap and permit intuitive knowledge to support formal learning, Resnick identifies four kinds of mathematical reasoning that emerge in developmental sequence, and she proposes, in this and other lines of work, some principles that can help teachers build upon and sustain their students' intuitions during formal instruction.

The four kinds of mathematical reasoning that Resnick discusses are the basis for a theory of "layers" of mathematical knowledge. This theory describes children's progress from intuitive understanding rooted in their knowledge of the physical world to an ability to reason about abstract entities in formal instruction. The most elementary layer of understanding is the "mathematics of protoquantities," in which children understand and can predict the effects of changes in amounts of material but do not engage in counting or quantifying. They may talk about a big house or many cookies or more juice, but it is not until they begin to develop understanding at the second layer, the "mathematics of quantities," that they talk about 3 houses or 8 ounces of juice. Here, they ascribe meaning to numbers and measurements in the context of dealing with actual objects and materials. In the "mathematics of numbers," numbers now make sense not only as adjectives but also as separate, abstract entities that can be manipulated and acted upon. Children can add 3 and 5, for example, without having to understand them in terms of, say, 3 cars and 5 buses; and they realize that 3 is less than 5 without having to compare sets of objects. This ability to conceptualize abstractions develops further in the fourth and final layer, the "mathematics of operators," in which not only numbers but operations and relations can be reasoned about. By this stage of understanding, children know that operations themselves can be manipulated; that, for example, if one adds 4 to a quantity and then subtracts 1 from the answer, the result is the same as if one had simply added 3.

These four layers, or types of mathematical thinking, do develop sequentially, but Resnick cautions that the late ones do not supersede those that go before. To the contrary, a student might engage in all four types of thinking while solving a single problem in arithmetic. What is most important about the sequential character of the four levels of reasoning is that each needs to be fully grasped in order to support and interact with the next. If classroom instruction can identify the levels at which students are able to perform and can guide them through all aspects of all four types of reasoning in mathematics, then, presumably, the troublesome discontinuity between intuitions and symbolic manipulations can close.

Other lines of work by Resnick suggest that children might proceed more easily along this cognitive continuum if instruction can provide a link between the familiar forms of learning through which their intuitive knowledge of numbers and amounts develops. Children acquire their intuitions by observing and interacting with the world around them. Their explorations are not structured or bound by rules but instead are spontaneous and inventive. In research on math as an ill-structured rather than a highly organized discipline, Resnick has proposed that arithmetic classrooms permit much the same kind of experimentation and discovery that go on before a child enters school. She recommends that students be encouraged to talk about math, work together to solve problems, use finger counting and any other physical aids they can devise, and compare multiple methods of solving the same problem.

Children acquire their intuitions by observing and interacting with the world around them.

Resnick's work suggests that students will discover and internalize mathematical principles for themselves if they have opportunities to handle and experiment with quantities and sets of objects, invent procedures for solving problems, talk about their own and other children's solutions, observe their classmates' methods of investigating numbers, and explore real-life situations involving arithmetic. Such activities help students to expand their knowledge and become more aware of their processes of learning until, with guidance and demonstrations from their teachers—but little direct instruction—they begin to link their experiences and their intuitive methods with the formal mathematical symbols and notations that can express numerical insights more precisely.

According to Resnick, such instructional innovations reduce the discouraging sense of abstractness that too abrupt a transition from intuitions to formality can generate. By continuing children's exploration of the physical world and gradually helping children to express their findings in mathematical language, the referents remain visible. In fact, says Resnick, "an explosion of interpretations" becomes possible when mathematical statements are seen as referring not just to numbers and operations but to all the actual things in the world that those abstract entities might represent. Easing the transition to formal learning in this way might guide children with less difficulty through all four layers of mathematical reasoning that Resnick describes as essential to a complete understanding of school math.

Teaching—A Complex Set of Tasks

Despite Resnick's emphasis on instructional innovation and the development of an inquiry-and-discovery approach to classroom teaching, she readily admits that more traditional techniques also succeed. Thus, it is interesting to note that other research at NRCSL, which closely compares the instructional methods of novice and expert teachers in actual classrooms, both identifies many ingredients and qualities of successful traditional approaches and also implies that they may be more "innovative," in Resnick's sense, than their appearance of direct instruction would suggest.

Though Gaea Leinhardt, who spearheads these classroom-based studies, does not look directly at the cognitive connection between concepts and procedures, much in her work relates to that connection. In examining the cognitively complex processes of teaching, for example, she has found that expert teachers build into their lessons several components that enable their students to build accurate mental representations of mathematical concepts and behaviors. In effect, these teachers find ways to guide learners, at least implicitly, through the layers of reasoning that Resnick has identified. They do so by a "layering" process of their own. Leinhardt explains, "a lesson given by an effective teacher who has been teaching for many years essentially contains layers of accumulated knowledge about the topic and how to teach it."

Each year, a good teacher adds increasingly rich layers of effective methods, terminologies, examples, and explanations to her teaching of a topic.

Each year, in each class, a good teacher adds increasingly rich layers of effective methods, terminologies, examples, and explanations to her teaching of a topic. The cognitive activity involved is at least as complex as that of a learner, but its goal is to build comprehension in other minds than the teacher's own. To accomplish that goal, an expert teacher develops strong metacognitive skills—those that allow her to monitor each lesson's progress and to make adjustments and repairs as necessary. She also learns how to manage a classroom full of children with minimum disruption, how to keep her instruction logically clear and easy to follow, how to remind students of old material and orient them to new, and how to signal transitions from one part of a lesson to another.

Leinhardt groups these skills and devices of teachers into categories, each of which represents a subcomponent of a lesson. *Routines*, for example, are behavioral steps that move lessons along without significant interruption. They become familiar to students early on, so that once a teacher signals a routine, it proceeds almost automatically. There are four kinds of routines: *management routines* take care of the physical movement of people or materials, permitting students to stand in line, pass out paper, share manipulatives, or hand in homework efficiently. *Support routines* are orchestrated for instructional purposes and consist of the rules by which students approach the blackboard, assemble into groups for discussion or problem solving, exchange papers for correction, or turn to appropriate sections of their texts. *Exchange routines* are the rules of verbal communication, especially in the service of the topic being discussed. According to Leinhardt, exchange routines not only let students know the usual procedures of communication but also signal changes in those procedures. An expert teacher, for example, will prepare her students for something out of the ordinary by saying, "Now we are going to do something a little different," or "We usually do things this way, but now I want you to try a new method." Finally, *learning routines* are those that keep students' attention on the topic. Leinhardt believes these need to be studied more systematically, but she characterizes them as questions and cues that elicit appropriate subject-matter insights from students. For example, while demonstrating a procedure at the blackboard, a teacher might ask students to describe out loud the steps in her calculation or to identify and explain her deliberate errors.

Classroom routines are supported by instructional *scripts* that both cover the topical material to be taught and move the management and support routines smoothly along. Teachers constantly revise and update their scripts on topics that they cover frequently. They also form, for each segment of a lesson, content-based *agendas* that reflect their instructional goals and plans. Agendas are usually not written down but exist in the form of mental notes about which part of a topic the students need to learn, what might cause them problems, how the teacher can assess their comprehension, and what actions she will combine to get the material across. The final teaching component that Leinhardt has studied, and in some ways the most important, is *explanations,* which she has observed can either be directly expository or can indirectly encourage students' own discovery and insight.

Leinhardt has examined lessons, routines, scripts, agendas, and explanations in both mathematics and history classrooms, comparing expert and novice teachers in order to reveal, through differences in their approaches, just what it is about the experts' instruction that works. Leinhardt characterizes the overarching goal of her research as an understanding of "the way in which knowledge can be acquired and built under the guidance of a teacher."

Leinhardt usually elects to study a topic that represents a pivotal moment in learning. Fractions, ratios, and proportionality, for example, mark a point at which students move into an important expansion of the number system and can either gain considerable understanding or become deeply bewildered. While researching the topic and learning its instructional requirements and pitfalls, Leinhardt also identifies expert teachers who conduct classes in the relevant subject area. Experts are defined as teachers who have had success with students for many years and who are also regarded by their administrators as extraordinarily effective. Novices are usually preservice teachers.

Once Leinhardt understands the topic and has recruited teachers—which may take a year—she begins recording each teacher's instruction, gathering from five to 90 days worth of lessons on videotape and then coding, analyzing, and interpreting their content. In addition, her research team conducts in-depth interviews with the teachers about their professional development, career choices, and subject-matter knowledge.

The significance of Leinhardt's studies and methodology are especially well illustrated in her comparisons of expert and novice teachers' conduct of lessons in fractions. For this work, she studied generalists (teachers who teach all elementary school subjects) in public school classrooms with 25 to 30 students each, an environment Leinhardt regards as "the acid test" for assessing instructional methods and performance. She found, in general, that the expert teachers were far more skillful than novices at all aspects of their job, from classroom management to the construction of clear and thorough explanations. As Leinhardt writes in a paper entitled "Expertise in Instructional Lessons: An Example from Fractions," expert teachers

> keep lessons flowing and are aware of and in tune with what their students are learning. The teachers manage homework, seatwork, demonstrations, games, discovery projects, discussions, and drill with fluidity and consistency. Time is always treated as a valuable resource and is not squandered in getting set up and in making multiple unintended false starts. . . . Expert teachers also *teach* very well. They give detailed, complete explanations and demonstrations, and provide rich mathematical experiences for their students.

None of this seems at all surprising. It is what one would intuitively expect of a truly effective teacher. But the contrast with the efforts of novices both reveals the high level of skill required in managing all these tasks in a single lesson and offers a detailed account of each skill that contributes to expertise.

For example, just the comparison of teachers' agendas for lessons in fractions revealed the experts' deeper understanding of what their students needed from instruction and how the teacher might provide it. Researchers interviewed both experts and novices about lessons they were planning to teach and found that, although their responses were of generally equal length, the content differed dramatically. Experts specified the instructional moves they intended to make and the actions they would require from the students. They explicitly designed their lessons to flow smoothly and logically, and they identified points at which they planned to check the lesson's effectiveness and, if necessary, adjust its logical flow.

Novice teachers' agendas were never so specific or so detailed. An expert might say precisely how she planned to introduce a new topic (such as adding fractions), relate it to a recent one (such as equivalent fractions), make use of manipulatives or drawings that could clarify crucial concepts, and assess her students' comprehension by having them work on problems at the blackboard. A novice, on the other hand, might say of a similar lesson, "I'm going to go over yesterday's homework on the board. It would probably be good for this class. I don't know how many I am going to go over. There are 36 problems. But I'm going to see how it goes. If they're all getting them very quickly, then we'll move on."

This novice, like others studied by Leinhardt's group, expressed no strong mental representation of her own lesson or the topic she intended to cover. As Leinhardt points out in her paper, "The novice had taught a lesson on reducing fractions which had failed, had retaught the same lesson, and had assigned homework. Her entire set of activities for the day was slated for going over the homework. Even though she stated she might 'go on,' she had no idea of what [she] would go on to."

What is implied by the expert teachers' richer, more flexible, and more varied approaches and lesson components is that these teachers have succeeded in forging a solid link between their own conceptual and procedural forms of knowledge. They not only have a deeper understanding than novices about the subject matter and the cognitive problems it can present but a far stronger ability to anticipate and surmount those problems, monitor their own effectiveness, and orchestrate the myriad small activities that surround classroom teaching and learning. In fact, as Leinhardt has documented in many classrooms, these expert teachers are often led by their conceptual understanding of their subject and their craft to incorporate many of the techniques Resnick's work identifies as fruitful: discussion, discovery, collaboration, manipulatives, and guidance toward a grasp of concepts. Leinhardt, pointing out that the experts she studies nevertheless do teach in very traditional settings, recommends that future research investigate expert teaching as it takes place in more inquiry-oriented classrooms; that it analyze when and how to teach procedural as well as conceptual knowledge; and that it study the effects of traditional and discovery-based teaching styles on different topics in math and other subjects. She urges, "Let us find out how much problem solving and inquiry we can get out of straight didactic teaching, how much computational fluidity and accuracy out of an inquiry approach, and then figure out when to use which kinds of approaches."

Though some highly exceptional teachers are always around to ignite students' curiosity and determination, widespread education reform cannot depend on their genius alone.

Expertise in teaching, regardless of the setting in which it occurs, is indispensable to any efforts to raise educational standards and expectations in this country. Though some highly exceptional teachers are always around to ignite students' curiosity and determination, widespread education reform cannot depend on their genius alone. If only a relatively few teachers teach well, only their students and a few gifted others will learn well. In order that excellent teaching—and therefore excellent learning—might take place in more classrooms, Leinhardt has also devoted much of her time to questions of teacher training, assessment, and professionalism. For example, she has collaborated in the Carnegie Forum's Teacher Assessment Project at Stanford University, an effort to develop improved principles and procedures for measuring the skills and effectiveness of practicing teachers. This work gave rise to a project with the Connecticut State Department of Education on the design and development of a scoring system for a semi-structured interview to be used as a performance-based assessment of teachers seeking licenses in that state. Leinhardt has also been a key participant in a collaborative project at NRCSL that has brought researchers and practitioners together to build teacher professionalism and leadership in mathematics instruction.

Collaborative Projects Foster Teacher Professionalism

Two major, interrelated projects at NRCSL began directly affecting classroom instruction in mathematics in 1987 and 1988. They continue to be refined, expanded, and disseminated to additional schools and school districts. Both projects are collaborations between researchers and teachers, and in both the two groups' combined knowledge of learning and instruction has created dynamic, effective, and adaptable classroom reforms. Yet perhaps the main accomplishment of each project has been to establish conditions under which experienced teachers have been able to become leaders in education reform, carrying their impact far beyond their own classrooms.

The *Thinking Mathematics* project was begun with seed money from OERI; the St. Agnes School project has been substantially supported with OERI funds throughout its application and dissemination efforts. Both projects are based largely on earlier research conducted under OERI auspices in NRCSL, and both represent a true partnership among government, research, and education practitioners to further a substantive understanding of learning processes and an application of that understanding to improvements in education.

Thinking Mathematics Project

> For most of my colleagues, researchers are viewed as ivory tower people not connected with reality. When they would come to the schools, teachers would turn up their noses. [Yet] I've found teachers eager to receive valid, real-class research that we ourselves have tried out. I think that there is a great hunger on the part of teachers for ways to solve the problems they see every day.
>
> —Alice Gill, elementary mathematics teacher

During the 1987–88 school year, NRCSL mounted a dissemination effort that was meant, at first, to be accomplished through the translation of research findings, by teachers, for teachers. The model upon which it was based was that of the American Federation of Teachers' (AFT) successful Educational Research and Development (ER&D) program, in which teachers called Local Site Coordinators (LSCs) synthesized and disseminated research for colleagues in their school districts on such topics as classroom management and cooperative learning.

The new collaboration, however, was the first ER&D attempt to synthesize cognitive research on the content of a given discipline. NRCSL's interest in working with the AFT to convey research on mathematics learning to the union's membership was motivated first, as NRCSL's William Bickel explains, "because practitioner groups such as the AFT are skilled at communicating to their own communities, but we're not. To the extent that we could establish a relationship and dialog with the AFT, we could reach the larger constituency that they represent " AFT responded well to the idea, says Bickel, because of an equal concern about "the conditions of mathematics instruction in the schools. . . . We believed, and the AFT agreed, that there was new math research knowledge that could help."

Most of the research to which Bickel refers had to do with children's intuitive, preschool knowledge of mathematics and with ways in which instruction could build upon this knowledge, promote discovery instead of leaning heavily on repetitive drill and practice, and foster reasoning and problem-solving skills. The joint AFT/NRCSL goal was to help teachers apply the research findings in the classroom. The plan for reaching the goal was to commission cognitive science experts to write articles synthesizing recent math research and then to recruit expert math teachers from the AFT to translate those articles for other practitioners. The translators—called Visiting Practitioners—would come to NRCSL for a summer workshop at which they would read, discuss, and prepare to disseminate the research synthesis.

The plan hit a snag when its initial one-sidedness became apparent. The researchers, in designing the project and the workshops, focused primarily on research findings that might improve practice, but they attended little to the world of practice itself. The readings they gave to the Visiting Practitioners had much to say about concepts and principles that could affect instruction; but they did not prescribe actual reforms or methods, nor did researchers always interpret findings in the same way. The Visiting Practitioners, though they had decades of practical and intuitive knowledge about instruction, were unfamiliar with the standards, language, and procedures of the "ivory tower people." As a consequence, what was meant to be a collaboration came to resemble a tutorial, with expert mathematics teachers placed unwittingly in the role of the researchers' students. These "students," in carrying our their reading and translation assignments, were not urged to question research findings, interpret them in the light of their clinical expertise, or suggest refinements.

Thus, the first AFT/NRCSL attempt to launch a productive, extended dialog became, almost literally, a monolog. Gaea Leinhardt videotaped the sessions that took place in that first workshop and coded them, as she recalls, "with respect to issues like who was speaking, who initiated it, whether we were talking about math, whether we were telling anecdotes or talking about the politics of schools." She was looking for lively discussion, she explains. "What I was hoping to see over time was an increase in the amount of talk that was being controlled and actually spoken by teachers and an increase in the amount of mathematical discussion." What Leinhardt found instead was that most substantive discussion that summer was initiated and led by researchers. The teachers said little.

The results of that workshop led the researchers to realize that they needed to say less and listen more, which meant they had to create conditions under which the Visiting Practitioners would be motivated to speak. As Leinhardt says, "to get teachers to talk about how to actually teach a substantive topic in math is quite difficult. You must give them time to talk, and you must make sure that it's a very supportive environment in which to bring those topics up. Their assumption may be that researchers know exactly how to teach this, which is not true. We often haven't the foggiest idea."

The results of that workshop led the researchers to realize that they needed to say less and listen more.

By the next summer's workshop, for which a second group of Visiting Practitioners was recruited, the new plan, Leinhardt says, "was not to understand research articles and see how they could be applied to the classroom, but to understand the nature of a classroom lesson and see how research might support the goals of that lesson."

Calling upon the Visiting Practitioners' clinical expertise added the key element to the collaboration. The project already was the only content-based ER&D effort and the only one to attempt an extended dialog between practitioners and researchers. But the dialog could succeed only if it were conducted as a conversation among equals, with the researchers as willing to learn from the teachers as to instruct them. By degrees, the shift in focus from the researchers' world to the teachers' world made way for the Visiting Practitioners to become the researchers' colleagues and coauthors, eventually taking the lead in preparing the *Thinking Mathematics* series, volumes of teacher training materials that combine the best insights of both research and practice, while adhering to the standards of the National Council of Teachers of Mathematics. The volumes that have been issued so far cover counting, addition, subtraction, multiplication, division, and problem solving.

Alice Gill, a 22-year veteran of the Cleveland Public Schools, was one of the teachers recruited for the 1989 summer workshop where the new clinical emphasis took hold. Gill, a generalist who taught all subjects in second and third grades, says, "I plodded along with traditional teachings, but I was always searching for better ways. I wasn't happy with what was happening in my classroom." Gill was not the only one in her school who was discouraged. The year before she joined the collaboration with NRCSL, she recalls, "A staff-led team began to work on revitalizing the school. More than 50 percent of the kids in kindergarten through third grade were getting D's and F's in math. That was startling. Everybody thinks elementary math is easy."

When Gill learned that NRCSL was looking for collaborators, she was both excited and apprehensive. She already had been a Local Site Coordinator for AFT for 3 years, but this time, she says, "the call for applications said that they wanted teachers with a math background, which I didn't have. I called to ask about that and was encouraged to apply." Today, Gill feels "the project is probably better for having someone like me, without the deep math background. What we produce has to be disseminated to people like me. We have to ask, what's daily life like for the teacher who does more than teach only math? There's a different way of looking at things when you have a math background than when you teach eight subjects a week."

That second summer, the project began to produce the first volume of *Thinking Mathematics*, on counting, addition, and subtraction. Teachers who applied to the project were asked to review some of the research and to design lesson strategies as part of the application process. The five who were chosen to be Visiting Practitioners—including Gill—continued reading research and devising applications so that they would be prepared, by summer, to enter a dialog with the researchers. As William Bickel and Rosemary Hattrup write in their account of the project, a paper entitled "Paths to Professionalism," this early emphasis on lessons "placed the conversation on the teachers' home turf and provided the opportunity for the teachers to examine the research through the lens of their own classroom experience. It was the collaborative's hope that the dialog, rooted to classroom expertise at the outset, would begin more quickly . . . and that the teachers' clinical knowledge would be . . . reflected substantively in the conversations as well."

The new Visiting Practitioners did engage earlier and more substantively in dialog with the researchers, but they still were tentative in their linking of research to practice. According to Bickel and Hattrup, "Notions such as building on the students' own knowledge and the acceptance of multiple correct solutions (and sometimes answers) represented fundamental departures for many of the teachers. . . . The sense of unease was aggravated by the press of the schedule." These teachers were therefore entering with some apprehension into the very process that research suggested they should lead their students through. The teachers' credibility—which eventually came to illuminate the *Thinking Mathematics* materials, the teachers' own classrooms, and their relations with colleagues at pilot sites—came directly out of their firsthand experience with bridge-building between the clinical and scholarly worlds. They were able to link the practical, intuitive knowledge that is based in experience with the formal, theoretical knowledge that derives from close, disciplined studies of cognitive phenomena. This bridge-building experience is called "sense-making" by researchers. Things do not make sense until they are put into practice, refined, and adapted—until one can walk freely back and forth between the two worlds and their related but differently based concepts. The same is true for students, who must learn to relate the formal knowledge they gain through instruction to their lives beyond school walls.

Things do not make sense until they are put into practice, refined, and adapted.

True sense-making began for the Visiting Practitioners when they started pilot testing the *Thinking Mathematics* materials in their own schools and school districts. They put new methods into practice, based on instructional principles derived from their knowledge of research. These principles, which they identified in collaboration with the researchers, included the following means of linking abstract concepts to concrete referents: building on students intuitive knowledge; presenting students with situational story problems; making considerable use of manipulatives; stressing the acceptability of multiple solutions to problems; requiring students to explain and justify their procedures and answers. Other principles that the Visiting Practitioners applied had a somewhat different focus—instructional flexibility. For example, the Visiting Practitioners worked on developing the metacognitive skills Leinhardt had observed in expert teachers; that is, the ability to monitor their students' comprehension constantly and to adjust their instruction as needed. They also relaxed their notions of the traditional curricular hierarchy that assigned math topics grade by grade and began to cover some topics earlier than before. Finally, they shifted their priority from quantity to depth of material covered, often extending by a matter of weeks the time they spent on important material.

In addition, the Visiting Practitioners conducted in-service sessions and discussions aimed at sharing new principles and methods with colleagues. Thus, their goal was not only to improve their own instruction but to build a culture of professionalism among their peers.

For Alice Gill—one of the overly busy generalists for whom *Thinking Mathematics* has been developed—both processes were dramatic. "I came back to my school, and the first thing I had to do was to bury my textbook. My goals were so different from what the text was after—getting kids just to learn basic facts and perform computations. My new goals were to produce kids who could think about math, solve problems—who really had confidence. And I saw all of this happen in my classroom. . . . Kids came up with *so* many ways of reaching right answers. Kids who had done nothing became contributors. What I saw was so much more than I would *ever* have thought these children could do."

The teacher is the link between the intuitive and the formal, between the students and the research that can benefit them.

When Gill began disseminating results of her summer work to teachers in her school district, she found that task, too, very different from her past ER&D work. "You can do a unit on effective teaching of rules and procedures," she explains, "and then the teachers can try it. But when you're developing radically different math instruction, it is necessary to do some modeling in the classroom and to have teachers interact with each other about what's happening."

Both Gill and the other Visiting Practitioners thus discovered the importance of a culture of professionalism. "Before," says Gill, "I would make independent efforts at reform, but even the things I thought were great were not so great. I didn't have the math knowledge to see that. I think teachers need more math knowledge, and I think they need to understand the NCTM standards; but it is going to take quite a dissemination effort to get them to buy in. What happens is, teachers who might decide to experiment might run up against district requirements that slap them down. They have to teach to standard, traditional tests. They revert back to the conventional ways of teaching." Gill and others in the AFT/NRCSL collaboration hope that leaders and role models who can demonstrate the success of new approaches to math instruction will appear increasingly among the ranks of teachers and gradually gain the backing of administrators and district management.

The role of the teacher, as the Visiting Practitioners' experience shows, is crucial to any system-wide changes in instruction. Through developing, piloting, and reflecting on the *Thinking Mathematics* materials, the teachers have been able to appreciate the appropriate and powerful ways in which their clinical insights can shape reforms in the collaboration itself, in their schools, and among their colleagues. Almost no researchers are likely ever to be in as good a position to gain such well-rounded an expertise—a professionalism that comes both through close familiarity with researchers as colleagues and through years of classroom experience. The teacher is the link between the intuitive and the formal, between the students and the research that can benefit them. Yet, in the past, as one Visiting Practitioner told Bickel and Hattrup, "attempts at 'professionalizing' teachers [too often] have focused on giving them 'teacher proof' programs that were supposed to succeed in spite of the teachers. This collaboration, on the other hand," said the teacher, "has truly professionalized teachers by trusting them to build the design necessary to influence classrooms." The same might be said for NRCSL's other major teacher-researcher collaboration, the St. Agnes school project.

St. Agnes School Project

> Before, I taught intuitively. Now it's grounded in research. It validates my knowledge of student learning, my observations, my planning. If I design strategies based on research, I can move them along faster. I love this research.
>
> —Victoria Bill, elementary mathematics teacher

Victoria Bill began reading research on mathematics education in the summer of 1987—the same summer that the AFT/NRCSL collaboration held its first workshop. A team of researchers, led by Lauren Resnick, had been conducting classroom-based experiments at St. Agnes, the inner-city parochial school where Bill taught arithmetic to elementary students. Bill became acquainted with some of the researchers, and eventually Resnick offered her a stipend and a chance to spend her summer reading a body of research on children's informal understandings of arithmetic principles. Bill agreed, interested in the possibility that research might offer antidotes to the difficulties she sometimes had in reaching her low-income, mostly minority students. "I would try anything," she says.

The only condition on Bill's arrangement with Resnick was that the two of them meet once a week to discuss Bill's reactions to articles and findings. Resnick, who needed a teacher's clinical insights for a strand of her NRCSL work, hoped they both would benefit from their conversations. She also felt that if she could help Bill apply research to her teaching, it would be a way of repaying St. Agnes for the school's cooperation.

"I met with Vicki Bill regularly," Resnick recalls, "and over that summer, she started building an interpretation for herself. It included some pretty radical things to do."

Bill, like many teachers in this country, had been trained to instruct her students directly in the rules and procedures of computation, to lean heavily on drill and memorization in imparting basic arithmetic skills, to teach what standardized tests would require, and to keep a quiet and orderly classroom in the process. But, Resnick explains, the research Bill was reading suggested "that if you stopped directly teaching the basic addition, subtraction, and multiplication that are the core curriculum of the first three grades of school, there was a very strong prediction that the kids would invent and use the underlying principles for themselves." This was what was "radical" about the research that Bill read. It called for a whole new approach to formal instruction, one that would build upon rather than ignore preschool children's intuitive, experience-based understanding of mathematical concepts. To Bill, it meant that conventional techniques she had been familiar with for years would have to be replaced. She concluded this from the research, but not from Resnick. "I wasn't being told I had to change, or that what I was doing in my teaching was bad," Bill recalls. "Lauren was just saying, 'Read this research and think about it.'" The more Bill did that, the more validated she felt despite her apprehensions. "What was really a good feeling," she says, "was to read about everything that I had discovered on my own, methods I had seen children using to solve problems. I didn't have formal names for them, but I had recognized them as sophisticated kinds of thinking."

Among the techniques Bill had seen her students using were counting on, counting all, fact strategies, and *MIN,* which children develop sequentially in that order. "In *counting all,*" Bill explains, "children simply count the number of objects in each of two sets in order to find the total in the two sets. *Counting on* is a shortcut—a device that lets children find the total number of objects in two sets without counting the first. If they see that there are three in the first set—or any number up to about five—then they just start from the three, going 'four, five, six' until they have the total for both sets." In order to count on, children must first have the concept of numerosity, which is the understanding that the number three identifies the quantity of a set with three objects in it. They must also understand that the order in which objects are counted is irrelevant to the total quantity. So when a teacher sees children move from counting all to counting on, she knows where they are conceptually. *Fact strategies* and the *MIN* strategy are further refinements of counting on, which provide additional signposts for teachers.

Despite the affirmation Bill gained by reading research, she sometimes found it "laborious" to grasp and discuss its findings. Not only were the standards and language of the research world new to her, but so were its collaborative aspects, which characterized her conversations with Resnick and occasional other researchers. "I was never part of a culture of collaboration before, where people would discuss and organize their approach to a problem together. There is nothing more stimulating," Bill declares, "but it is not part of a teacher's experience."

To Bill, the teacher's experience was to teach in isolation, work around the clock, and talk with her colleagues only in generalities about students and working conditions. "I don't think teachers have a lot of time to sit back and look at everything," she says. "Our lives are too hectic. I mean, you teach all day, and you don't stop for a minute, and then you go home to your family and do more work at night to get ready for the next day. This collaboration with researchers gave me the opportunity to sit and really think about teaching."

As a consequence of the schedule she describes, Bill had some qualms about her level of math knowledge and her ability to apply what she was learning from her reading. "I knew when I walked in here," she explains, "that there were many ways that I was not prepared, not educated." Though she agreed with researchers from the beginning that teachers needed more math, she disliked the assumptions that some made about her own background. "I taught for many years before I entered the world of research," she says. "And I considered myself good." Though she was aware of a need for a deeper grasp of mathematics, Bill knew that her clinical knowledge was at least as important. She was an expert on what she calls "the nitty-gritty details and glitches, the human chemistry of the classroom." It was because of this expertise, and Bill's determination to grapple with the instructional challenges that research presented, that Resnick had high expectations for what Bill would create out of her summer's work.

Bill's confidence grew the more she read and discussed. Each week, she and the researchers would meet and talk about "various topics—addition, subtraction, letting children be inventive, letting them talk with one another about math." As the fall school term approached, Bill committed herself to introducing effective reforms in her classroom instruction. The only question was, how? "The inventiveness that you want to see in children—how can you bring that in the classroom?" Bill asked herself. "How can you do that in a step-by-step way? For children, you have to be very structured. How could I structure this and not risk the kids' welfare if I made a mistake?"

"The inventiveness that you want to see in children—how can you bring that in the classroom?"

Bill worked closely with Resnick on designing the reforms she would adopt. Some of her fears were eased by a guarantee that if her students did not progress, the researchers would personally tutor them until they could meet the school's requirements. Nevertheless, Bill was apprehensive. "I felt like I wanted a script," she recalls. "And the researchers were saying, 'We don't have anything to give you. Go ahead.' Then, when I went back to the classroom, things certainly looked very different than during the summer. To be honest, everything I read did not fall into place until November, December."

But Bill began in September to change the way she taught arithmetic. She introduced many more manipulatives than she had ever used, creating opportunities for children to count, sort, match, and regroup objects in their explorations of numbers and amounts. She carefully designed her lessons "so that they were sequenced for them to make discoveries," and in doing so she was able to build deliberately upon the developmental patterns she had always seen—the progress from counting all to counting on, for example. But her first efforts "were still pretty much teacher guided. I was still telling my students what I wanted them to know, rather than helping them find it out for themselves."

Bill, in effect, had set out to test the research-based prediction that children would discover mathematical concepts on their own if teachers stopped explicitly teaching those concepts. But it was not until Resnick visited her class that she began to see how much she still was stating rather than demonstrating. "When Lauren came for the first time," says Bill, "she told me it was not what she had expected. One of her comments was, 'I expected more talking,' and here I was thinking that two kids talking together was pretty good. I was used to this silent room."

By degrees, Bill designed a set of teaching strategies that reflected many of the principles applied by the AFT's Visiting Practitioners. In fact, Bill and Resnick defined many of those principles during Bill's first year of redesigning her instruction, and they shared them with the Visiting Practitioners during that project's second summer workshop. The principles all were aimed at nurturing the habits of thought and feelings of confidence that would establish young learners, in their own and other people's minds, as mathematical reasoners. By November and December of 1987, when Bill felt her knowledge of research start to fall into place beside her clinical expertise, her incorporation of these principles had thoroughly revamped her classroom and taken her far beyond her initially cautious reforms. She did not, however, lose her concern for orderly routines of the sort Gaea Leinhardt's classroom research identified. "I had to tighten my routines," Bill says. "I developed specific rules for manipulatives—the children learned where to keep them, how to put them away, not to handle them until I gave the signal. Every move was efficient. Those things make or break your teaching, no matter how innovative it might be."

The specific principles on which Bill based her instructional changes are outlined in a paper she wrote with Resnick and others entitled, "Thinking in Arithmetic Class." They are:

1. Develop children's trust in their own knowledge. This leads to an effort to extend children's intuitive, pre-instruction knowledge through familiar learning methods, including finger counting and manipulatives, the use of everyday language to describe mathematical relationships and problems, and an emphasis on multiple procedures for solving problems. The latter, in particular, encourages children to invent numerous strategies of their own for reaching the same conclusion.

2. Draw children's informal knowledge, developed outside school, into the classroom. Specifically, children are encouraged to use counting extensively in story problems, especially about real-life situations. This helps them to quantify their intuitive knowledge, relate it directly to the use of numbers as symbols, and prepare for the connection between their informal knowledge and the formal notation they soon learn.

3. Use formal notations as a public record of discussions and conclusions. When the teacher uses standard mathematical notation to record children's conversations about math, carried out in everyday language and rooted in well-understood problem situations, the notations take on a meaning directly linked to children's mathematical intuitions and experience.

4. Introduce key mathematical structures as quickly as possible. This means explicitly laying out for children the mathematical situations that represent their initial, intuitive knowledge—that is, introducing them right away to addition and subtraction problems, the composition of large numbers, and strategies such as subtraction by regrouping, and then letting them develop mastery over time. This, as "Thinking in Arithmetic Class" notes, "constitutes a major challenge to .... the notion of learning hierarchies—specifically that it is necessary for learners to master simpler components before they try to learn complex skills."

5. Encourage everyday problem finding. Because children need far more practice solving math problems than they can obtain in the classroom, and because they need also to understand how ubiquitous math is in everyday life, they are encouraged to identify and solve the problems that surround them outside of school.

6. Talk about mathematics, don't just do arithmetic. Because discussion and argument are essential to children's development of critical thought and to their ability to justify their ideas, students routinely discuss difficult problems that the teacher poses. They talk about what information the problem provides, what remains to be discovered, and what strategies might be used. Then they work together in teams to solve the problem, and they justify their solutions to the class, generating comparisons with other teams' solutions and further discussion about the nature of the problem.

These six principles, write Resnick, Bill et al., were intended to "engage children from the outset in invention, reasoning, and verbal justification of mathematical ideas .... Our goal was to use as little traditional school drill as possible in order to provide for children a consistent environment in which they would be socialized to think of themselves as mathematical reasoners and to behave accordingly. This meant that we needed a program in which children would successfully learn the traditional basics of arithmetic calculations as well as the more complex forms of reasoning and argumentation."

The changes in Bill's students were dramatic. Her first-grade students—nearly all of them low-income, minority children who in kindergarten had done poorly in both math and reading—entered her classroom with scarcely any formal skills. Most could not count to 100, or even across the boundaries of decades (for example, from 29 to 30). Only a half-dozen could solve simple addition problems, even with the aid of finger counting or manipulatives. But by December, nearly all could solve both addition and subtraction problems, half of them by using procedures they invented themselves. By the end of the year, all of Bill's children were performing well, and some were even able to handle multi-digit addition and subtraction problems. Their standardized test scores had risen from the 25th percentile to the 80th, with even the lowest-scoring child comfortably ensconced in the 66th percentile.

Children's confidence and enthusiasm also rose to unprecedented levels during Bill's first year of innovation. Her students turned in their homework without prodding, often asked for extra math time, showed off proudly for visitors to the school, and eagerly brought problems from home. Their parents, most of whom belonged to a population that is typically disaffected from schools, began to notice their children's delight in math and problem solving, and they asked Bill to incorporate their daughters' and sons' "found" problems into classroom lessons.

The implications of Bill's reforms, which are now in their fifth year of refinement and are being disseminated to the classrooms of 38 other teachers, have in Resnick's view begun to represent "a new theoretical direction in our thinking about the nature of development, learning, and schooling." In "Thinking in Arithmetic Class," Resnick et al. associate this new direction with "the view . . . that human mental functioning must be understood as fundamentally situation-specific and context-dependent, rather than as a collection of context-free abilities and knowledge. . . . As we developed our program, we found ourselves less and less asking what constitutes mathematics competence or ability for young schoolchildren, and more and more analyzing the features of the mathematics classroom that provide activities that exercise reasoning skills."

Teachers must teach each other how to introduce changes in their instruction.

The importance of classroom features and of the social culture in which learning takes place is exactly why the classroom teacher, with her experience of the existing culture and her ambitions for a new one, is the key player in education reform. It is also why, as both Bill and the AFT Visiting Practitioners have discovered through their dual experience as reformers and disseminators of reform, teachers must teach each other how to introduce changes in their instruction.

Bill, like the teachers in the AFT/NRCSL collaboration, had to go through much the same process that research called for children to navigate—an integration of her intuitive, practical knowledge of the classroom with the formal, analytical findings of education research. A crucial part of a similar process for students is continuity with their familiar ways of learning and a gradual incorporation of those familiar ways with new ones. Bill's introduction to new ways was anything but gradual. She was suddenly immersed in an unfamiliar world, reading accounts of work whose supporting theories and operative hypotheses she had never before encountered explicitly. "No one could say to me, 'I know what you're going through,'" Bill recalls. "When I took what I learned into the classroom, no one could say, 'I know what it's like not to make any progress for three days.' No one could say, 'Give it a couple more days and you will be surprised at the progress.' Or 'Try this; it worked for me.'"

Bill, with her knowledge of two worlds, is now a model for more than 40 teachers to whom she has introduced her new methods. "They think, 'If she can do that with *her* kids, who have never performed well before, I can certainly do it with mine,'" Bill says. She is also a model for the researchers, demonstrating to them the limits of their own expertise and the need for broadening it. "I show the researchers how to consider the teachers' perspective," she explains. "They now tend to watch what I do and to say, 'If Vicki did this, she had to have a reason,' whereas, before, they might have advised me to do what they thought was best. Some of them never really realized the importance of certain pedagogical moves, language, techniques. I show them how I make connections between intuitive math and formal math happen for kids."

The same recognition of the need for leadership and professionalization among teachers characterizes three other collaborative projects with ties to NRCSL. Two focus on mathematics education and draw upon the same research—conducted at NRCSL and elsewhere—that informs the AFT/NRCSL project and the St. Agnes School project.

Thinking Through Language

Concerns of Research: Connections Among Knowledge, Reasoning, and Uses of Language

In most subject matters other than mathematics, learning and instruction proceed primarily through written or verbal communication, without additional support from a system of formal, symbolic expression. Such language-based exchanges provide opportunities for reasoning that are just as rich and challenging as mathematical discovery and problem solving; but in these matters, too, it is important to winnow out the valuable from the unproductive in both traditional and more experimental approaches. Levels of verbal literacy have fallen in recent years, while the literacy demands in the culture and workplace have risen. It becomes useful, then, to look at the nature of verbal communication in education, to see whether and how it cultivates skills that students will need in the real world, to identify its strengths and weaknesses, and to understand in detail the ways that it supports or impedes the construction of accurate mental representations of concepts. Like the investigations into mathematics learning that have already been described, research on language-based forms of learning and reasoning focuses both on students' existing knowledge and on the knowledge they need to gain from formal instruction.

Students need to learn three things: subject-matter content, how to learn content, and how to apply both content knowledge and learning skills.

When students enter a class in a given subject, they already understand something about learning, and they probably know something about the content of the discipline as well, either intuitively or from earlier instruction. Some of their content knowledge may be accurate, some not. Once they are in the classroom, students need to learn three things: subject-matter content, how to learn content, and how to apply both content knowledge and learning skills. Since most learning and instruction depend heavily upon written or oral communication, many of cognitive science's central questions arise in regard to every form of discourse—narrative, descriptive, expository, and argumentative.

For example, NRCSL research on texts and text comprehension investigates whether certain learning skills apply across disciplines or whether most learning must build upon background knowledge in the discipline. Which has greater influence upon learning—reasoning itself, or content knowledge? What goes wrong when readers misinterpret a text or fail to understand its content? Are there learning strategies that can make up for textual inadequacies? Other research projects at NRCSL—for example, on argumentation as a form of reasoning and on the use of argument in small groups—probe other fundamental questions about cognition. What are the mental representations and uses of argument? How are cognitive processes engaged and affected by argumentation? How might schools mount specific instruction on argumentation as a form of higher-order thinking? Does cognitive conflict within a group stimulate its members to learn more about an issue than they would if they all agreed?

What Does It Mean to Learn From Texts?

One important strand of research at NRCSL investigates the relationship between content knowledge and text learning abilities in the context of reading and language. The nature of language comprehension is at the heart of this work. Since so much of instruction is a matter of verbal communication, these studies provide a fitting context for exploring this core question.

Charles Perfetti, who leads this line of inquiry, conducted a decade or so of early work on reading ability, in which he identified the main components as word recognition, immediate memory of what was read, and related abilities to track textual sequences and syntax. He found that readers comprehend text successfully to the degree that these abilities are automatic and do not interfere with concentration. He concluded that "students who don't learn from reading don't have full control over these basic processes."

Beyond good reading skills, students in every subject need good texts, clearly and coherently written.

The fairly low-level skills—not "learning skills" but basic reading skills—are important in text learning but are not sufficient. These skills allow a reader to identify words and figure out the meanings of sentences, but they do not provide the connections to the subject matter. The question became what else is needed to learn from texts. This "what else?" question marked a shift in Perfetti's research from basic abilities to a concern with higher-order processes—"from asking how these basic processes work to asking how they connect with learning and whether that connection is different in different subject matters." Part of the answer to the question was obvious, he says. Beyond good reading skills, students in every subject need good texts, clearly and coherently written. They also need enough background knowledge in the subject to support a connection with what a text contains. If a student already knows what a text is about, Perfetti says, "he can read one sentence after another in a great flow, and you don't see any problem. But you show that same text to someone who doesn't have the background knowledge, and you'll suddenly see how implicit this text is—how much information is left out, or left up to the reader to fill in." Thus, reading is always and inevitably a matter of drawing inferences, a process that is made far easier if the reader has a reservoir of related knowledge from which to fill textual gaps.

Perfetti undertook text-related studies on the effects of background knowledge and reading skill in history, science, and even football. "In one study," he says, "we showed that students who did not have much knowledge about football could understand a story about it pretty well if they had good reading skills—but not if they were poor readers." A conclusion Perfetti drew from this held even across later research in history and science: "We found that if you had both knowledge and skills, your comprehension was very good. But if you had reading skills without background knowledge *or* if you had background knowledge without reading skills—either way—then comprehension was not so good." Nevertheless, Perfetti points out, it does not necessarily follow that content knowledge and skill are equally important to learning. Both have limits. "If someone gives me a technical article on subatomic physics, I'll have trouble understanding it no matter how skilled I am at reading. Ability can compensate only so far for a lack of knowledge. And vice versa. If you know a lot about a subject but can't read well, a text on that subject will remain to some extent incomprehensible. Texts are always going to compromise between leaving wide gaps that a reader has to fill with background knowledge and supplying every piece of information a reader needs to understand it."

Ability can compensate only so far for a lack of knowledge. And vice versa.

With the limits of both skill and background knowledge in mind, Perfetti turned to studies of the differences in learning from science and history texts. "We chose the domains to be dramatically different," he says. "The physics text, for instance, was written in flat, declarative sentences describing the structure of the atom, the behavior of particles, and so on. If you do a content analysis, you find that this particular science text has a logical, hierarchical kind of structure. The history text, which is about the United States' acquisition of the Panama Canal, takes a narrative form, describing many causal relationships between events."

As in the football study, Perfetti found both knowledge and skill important to readers' understanding of these texts. It was clear that basic reading ability, as Perfetti defined it in his earlier work, was a general skill, one that crossed the boundaries of subject matter and predicted good learning in science as well as history. In fact, it may have been more important in science, which is more difficult to read because it lacks the narrative flow of history and introduces more unfamiliar vocabulary and abstract concepts. The next question was whether some higher-order skill, closely related to basic reading ability, might also generalize across subject matters. "One candidate is the ability to make inferences from a text," Perfetti says. "Texts are more implicit than they are explicit. That is, they always demand that you provide some knowledge to fill in the gaps. So maybe drawing inferences, or understanding the implied content of texts, contributes to learning across domains."

After some studies, however, Perfetti is skeptical. Although certain inferences can be made directly from text—for example, the inference that a given pronoun refers to a given antecedent—"making inferences to fill in actual gaps in the text is very dependent upon knowledge. You can't do it if you don't have the background information. So at that level, inference-making is not likely to be a completely generalizable skill. . . . I guess the story continues to be that in order to learn things from texts, students have to have a certain amount of background knowledge."

Perfetti thinks that one reason it is so difficult to identify higher-order learning skills that apply across subject matters may be that texts always remain, to some extent, abstract. "Texts are not a very good way to make concrete the basic concepts that you want to communicate. You want students to be able to see what happens to an equation as certain values increase. That's where an interactive computer laboratory, for example, is really, really important. I would be curious to know whether any kind of reading ability that we measure predicts performance in deep science learning of the kind that hands-on experiments can generate."

What Perfetti is suggesting here obviously relates to the similar problem in mathematics instruction of linking concrete referents to abstract mathematical symbols and calculations. Just as that connection in math can be forged with the help of manipulatives, real-life story problems, and demonstrations, Perfetti believes a similar approach might be useful in science. He speculates that texts might contribute to a deeper scientific understanding if, for example, they described the activities of scientists more often. "I'm not convinced it's as important for the child to read some flat description of the atom as it would be to read a paragraph on the excitement of scientific discovery and how people have actually learned what the atom is like. That's the kind of thing that could be put in a narrative structure. Then the child could go to a lab to watch hypothetical models of the atom—see the electrons spinning, things like that."

Build both background knowledge and plenty of reading practice into classroom instruction.

Returning to the focus of his research, Perfetti says it has contributed "a clearer picture of how the trading relationship goes between basic ability and basic knowledge." He stresses that "to have identified both of these as important in learning does not mean that texts should resort to independent instruction on basic ability and basic knowledge." Instead, Perfetti recommends building both background knowledge and plenty of reading practice into classroom instruction. "Good instructional practice is aware of this," he says. "I think it's always been part of what good teachers do—assess background knowledge before beginning a lesson. Engage in a bit of dialog about relevant concepts. See what level of existing information emerges. Examine the text. Make sure it's coherent—that one sentence builds carefully on another, that you never have more than one knowledge gap between sentences, that the text is vivid and narrative."

This is a tall order, as Perfetti knows. Few textbooks in widespread use are able to fill it. Hardly any are "vivid," and most fail the coherence test. Another line of work at NRCSL has therefore raised the question whether it is possible for readers to develop learning strategies that compensate for the inadequacies of texts.

Reading, Comprehension, and Self-Explanation

Evidence that good learners can draw more inferences from their reading than the straightforward, text-based inferences described by Perfetti arose in the course of a larger investigation into the nature of background knowledge and knowledge construction in two science subjects, physics and biology. A considerable body of research had already documented how difficult it was for instruction to remove students' common, deeply held yet erroneous preconceptions about physical science phenomena; but less had been written or understood about initial misconceptions in biology. In order to test whether and how biology misconceptions might differ from those in physics, and whether they might also be easier to remove, Michelene Chi conducted empirical studies of eighth-grade students' learning from a text on the human circulatory system. Questions motivating the studies included: What is the nature of the knowledge structures students build as they learn? What causes students to misunderstand key concepts in a text on a given topic? Do misunderstandings arise out of students' erroneous background knowledge? Can instruction help students to reshape their existing knowledge structures?

Chi chose to study learning about the circulatory system for several reasons. Not only had the topic been identified as one of the five most important ones to be learned in biology, but, from an instructional perspective, it was a complicated topic to understand and one in which students were likely to have varied and unpredictable misconceptions. The topic also offered an opportunity to examine closely the causal reasoning involved in learning about the complex relations among circulatory system components and their functions. Finally, such a causally integrated system permitted researchers to locate points at which misunderstandings occur and to learn more about the nature of these misunderstandings.

Researchers examined eight textbooks that covered the circulatory system and created a composite set of text materials for students to read. Text analyses had revealed that all the texts contained numerous inadequacies, and even the most highly rated texts failed to explain the ways in which the behavior of local mechanisms of the circulatory system—that is, sets of interacting components such as cells, cell density, and membranes—served the functioning of the circulatory system as a whole. Another major textual fault was the failure to fully specify the functions of individual components of the circulatory system, a gap that made it very difficult to grasp the causal structure of the system.

According to Chi, when texts are seriously inadequate, "there are two alternative routes one can take to improve instruction. The most obvious one is to modify the text, but this seems overly difficult since there are so many texts out there." Furthermore, even though research data strongly indicate that incorrect intuitions about biology can be removed if texts directly contradict them and supply accurate information instead, "the problem is, you don't know which intuitions a given student will have. They're not predictable." Chi decided to pursue the second, less obvious alternative for improving instruction when she began to see that some students who were reading the inadequate circulatory system texts were—contrary to expectations that Perfetti's work might create—correctly inferring the functioning of system components even when the text did not supply that information either directly or indirectly.

Instead of attempting to analyze and revise texts, therefore, Chi began to investigate whether these successful students were applying cognitive skills that compensated for problematic texts. "We started to ask, 'How can students who hold incorrect mental models of the circulatory system or some of its parts be taught to construct accurate mental models from particular, inadequate texts?'" As the work progressed, and researchers took detailed, sentence-by-sentence protocols from students reading the troublesome biology text, evidence emerged that the readers who were able to induce the function of circulatory system components without any textual explanation were generating accurate self-explanations as they read. Researchers gave all the students the task of monitoring their understanding after each sentence they read, but, says Chi, "Monitoring in general is just an assessment of understanding. It is not the same as generating a piece of knowledge. Self-explanation generates pieces of knowledge."

As an example, Chi cites two self-explanations that one student generated after reading the sentence: *These substances (including vitamins, minerals, amino acids and glucose) are absorbed from the digestive system and transported to the cells.* The first fact that the student was able to induce, though the text did not directly state it, was, "Okay, so that's the point of what hepatic portal circulation is. To pick up these nutrients . . . ." The second self-explanation was prompted by the researcher's question, "Okay, why would you say that?" The student responded, "Well, because it says that it's absorbed from the digestive system—um, vitamins, minerals, and amino acids and glucose—and so that's why it's important to eat a balanced diet, or else your cells won't get the right vitamins, minerals, and amino acids and glucose." Both self-explanations—regarding the purpose of hepatic portal circulation and the importance of diet to the health of cells—compensated for gaps in the text's explanations.

Overall, Chi found that this process of self-explanation in successful students involved the ability to draw numerous low-level inferences that, cumulatively, led to the higher-level induction of circulatory-system components—in other words, the generation of that new piece of knowledge. Chi's most recent work identifies four kinds of low-level inferences that are necessary to self-explanations. These inferences link textual content with (1) common-sense knowledge, (2) episodic personal experience, (3) prior information from reading preceding sentences in the text, and (4) background knowledge in the topic. Chi stresses that these are "minute inferences" and that self-explanation is likewise "small." "It does not have to be complete at any level. Instead it builds up a network of understanding and allows knowledge to integrate."

Chi assumes that nearly all readers are able to make text-based, or syntactical, inferences of the kind described by Perfetti. But she believes that, in order to understand a broad and complex topic like the circulatory system they must also make these other, incremental kinds of inferences, drawing them from many sources. The eighth-graders in her studies were able to do so in response to "high-level prompts" from the researchers, questions that elicited the right kinds of inferences by "making the students work harder and prodding them to study the text material in a deeper way." Chi believes students can be taught to give their own high-level prompts and thereby to generate knowledge through this process of drawing several kinds of inferences. It is a possibility she is currently investigating. If self-explanation does prove teachable, it would readily cross the boundaries of subject matters and would therefore be a higher-order general skill of the kind Charles Perfetti has characterized as so difficult to find. Its implications for instruction would therefore be very great.

If self-explanation does prove teachable, it would readily cross the boundaries of subject matters.

Reading As Reasoning

Another perspective on the problem of mismatches between readers' background knowledge and the content of texts is provided by the research of NRCSL's Isabel Beck and Margaret McKeown. Unlike Michelene Chi, who feels that the unpredictability of students' misconceptions in biology makes it unlikely that texts could be revised to account for them, Beck and McKeown deal with the sufficiency rather than the accuracy of background knowledge. They chose to focus on text analysis and revision because of the ubiquitousness and overarching influence of texts, and they chose a broad subject area—elementary social studies—in which they felt texts were indeed subject to revision or to teachers' detection of their inadequacies. In addition, Beck explains, social science "represents the largest verbal curriculum in the schools. In it, you've got geography, history, anthropology, government—*and* it's a nonquantitative field, where texts will take a narrative form. At the elementary level, especially, the content of the texts represents the content of what children are learning. Some teachers may vary or supplement text coverage, but it is largely true that the books determine how, and how much of, a subject is covered."

Since there is no reading without content, or something to read about, Beck and McKeown emphasize the parallels between reading and reasoning, which also cannot take place except in relation to subject matter and existing knowledge. Thus, these researchers study reading as a form of reasoning they call "text processing," which requires learners "to engage closely with texts—monitoring comprehension, compensating for gaps in content, identifying ambiguities, categorizing details, evaluating arguments, tracking the narrative flow, and otherwise exercising considerable skill." Reading at this level, of course, is a higher-order business than exercising the basic set of abilities identified and analyzed by Charles Perfetti. It is exemplified by the students in Chi's studies who were able to induce concepts from text that did not describe or explain them. In the case of Beck and McKeown's studies, however, it is the researchers themselves who engage in this close, process-oriented examination of texts and reading in order to analyze in complex detail what successful reading entails and to diagnose problems that texts create for readers.

When Beck and McKeown set out to study how and why children learn, or fail to learn, from social studies texts, they focused on four segments of a fifth-grade text about the pre-Revolutionary War period in United States history. They regarded these segments—on the French and Indian War, the concept of no taxation without representation, the Intolerable Acts, and the Boston Tea Party—as representative in their failings and erroneous assumptions about readers' existing knowledge. McKeown says, "We asked students—before they read each piece of text—some things that we thought the text was assuming they already knew, and, as we suspected, the students didn't have this background knowledge. We also thought each piece of text itself was problematic. It was not coherent. It didn't hang together. It didn't explain things well." Not surprisingly, questions administered after children had read the text segments showed that they did not learn what the text intended them to learn.

None of this broke new ground in the field, since other researchers had observed similar failures of text and comprehension and had described them in general terms. The important difference in Beck and McKeown's work lay in the depth and specificity of both their analysis and their reporting, the precise detail in which they investigated just how and where student comprehension broke down and what sorts of confusion emerged in lieu of understanding. They regarded it as essential to find and then communicate in a deeper way what happened in actual interactions with text—to identify exactly why one piece of text works better than another instead of saying merely that one was clearer or better organized.

They investigated just how and where student comprehension broke down and what sorts of confusion emerged in lieu of understanding.

In the effort to delineate just what made a text clear or well organized, Beck and McKeown looked closely at texts that were neither. They performed their analysis against a backdrop of cognitive research on comprehension and learning from text. Just as cognitive psychology is concerned with "getting inside" the process of learning rather than with observing the outward manifestations of performance, Beck and McKeown's interest was with getting inside the instruction so that their findings could be understood in relation to the learning process.

The aspects of cognitive research that guided these researchers' analysis were recent understandings of the complex nature of the reading process, with emphasis on its interaction with a reader's knowledge, and characteristics of texts that can promote or impede comprehension. The analysis consisted of examining sequences of text material and hypothesizing the learning that seemed likely for young students based on judgment of the background knowledge that could be expected and on consideration of the effects of characteristics of text on the reading process.

Beck and McKeown began by identifying points at which confusion or incomprehension appeared in students' understanding of the American history texts they had selected. Then they conducted a cognitive, or text-processing, "simulation" of the students' experience; that is, they performed an in-depth, phrase-by-phrase analysis that considered what a child would do with a lesson or piece of text. The researchers, at each point in the text, would ask, What would come to mind as a student read the text? Where would they lose the narrative thread? What concepts were poorly explained and why? How could the text be improved? This fine-grained analysis, Beck says, was "an attempt to understand things below the surface, to get at the processes that we know underlie reading and learning and to describe them."

After the researchers identified weak points in both the content and the structure of the text, they began revising the text so that it did explain what they thought needed to be explained for children to understand why the

Revolution happened and what went on between the British and the Colonists. They also developed supplementary instructional materials that included concepts and factual material that students would need as background knowledge in order to compensate for textual gaps. The text-revision process was, in effect, a demonstration of the attention to detail that Beck and McKeown saw as necessary for textual clarity and coherence. Considerable change in text emerged as the researchers thought deeply and carefully about the interactions that should take place between readers and the text. A single textual passage provides a striking example:

The first sentence of the original text section of the French and Indian War said, "In 1763 Britain and the Colonies ended the seven-year war with the French and Indians." Beck says, "The first thing we say when we look at that is, there are two things wrong. First, it starts in the wrong place, with the end of a war that has not previously been mentioned. Second, it is unbelievably information dense. From that sentence, you're supposed to understand that a war existed, that it was fought for seven years, that Britain and the Colonies were on one side and the French and Indians on the other."

The revision of that single sentence generated seven sentences in its place. The first of these read: "About 250 years ago, Britain and France both claimed to own some of the same land here in North America." Beck comments, "I could go through and tell you why we did that and why we made every other change we made to that text. The major focus in that first sentence of our revision was to establish the primary agents and define the conflict between them—to motivate the war that the text is about. We also needed to set the time and place, which is why we specified North America and 250 years ago. We decided on saying '250 years ago' instead of 'in 1763' because we wanted to convey how long it has been since these events took place. Students reading '1763' don't reliably make that connection; they don't translate a specific date into an actual span of time that has elapsed since."

Beck also describes the thinking behind the next sentence that she and McKeown constructed, which was, "This land was just west of where the 13 colonies were." She explains the two reasons for its composition: "First, it keeps the colonies active in the reader's mind, and the whole point of these four consecutive text segments is to present and motivate the players involved in the events that led to the American Revolution. Second, we wanted to prevent a common misconception that the French and Indian War was fought over ownership of the 13 colonies themselves. Placing the disputed land beyond the colonies accomplished that."

After all four text segments had been revised and the supplementary materials completed, Beck and McKeown conducted further studies. In these, they gave some students the revised text, some the background instruction, some both, and some neither. Students who received only one or the other—the revision or the supplementary background lesson—did better than students who received the original text alone. But the students who comprehended the text most fully received both the revised text and the background lesson—in other words, both the knowledge required to understand the text and a text that had been made coherent and clear.

Students who comprehended the text most fully received both the revised text and the knowledge required to understand the text.

These findings—that both knowledge and reading ability (or read-ability) are necessary for learning—not only support Perfetti's similar ones but also confirm Beck and McKeown's hypotheses about *what* knowledge students must have to reason with and *what* improvements make a troublesome text accessible. Beck and McKeown discussed their deep text analysis in a paper called "Learning from Social Studies Texts," published in the journal *Cognition and Instruction.* They have described their text revision process in a second paper, "Revising Social Studies Texts from a Text-Processing Perspective: Evidence of Improved Comprehensibility," which appeared in *Reading Research Quarterly;* and they have led a workshop on text revision for 13 teachers.

Responses to the work of these researchers has been enthusiastic. The text analysis paper has appealed widely to researchers, teachers, and text publishers. Beck believes the paper's value lies in its detail. "We take a section of text and we talk through the text. We say, What might a learner learn from this? How would a learner know that this inference needs to be made? It's very specific, very concrete."

McKeown adds, "I've heard some reports of teachers reading this paper and having that kind of recognition—'Oh, now I see why kids have trouble with this!' And I think that's because teachers know a lot about these things at a general level. Most, I think, would say that the social studies textbooks they use are not the greatest, that students have problems with them. What we have done, by making the problems explicit, is to help teachers elaborate on what they already know, to put meat around the bones of their understanding." Beck and McKeown believe that the rigorous process by which they see into generalizations about texts and learning has maximum value only when they describe that process as thoroughly as they pursue it, making their own work a fully comprehensible text for both the world of practice and the world of research.

Argument, Inference, and Learning

All NRCSL work on texts addresses the fact that full comprehension of their content inevitably requires readers to make inferences. Perfetti, noting that every text is by nature incomplete, identifies the ability to draw syntactical inferences as a low-level general learning skill. Chi speculates that the cumulative effects of many minute inferences from many sources may generate new knowledge that compensates for serious textual gaps and inadequacies. Beck and McKeown both demonstrate and explicate the inferential processes involved in a close reading of texts. What yields a full understanding from texts is what Beck and McKeown call text processing and what Chi calls self-explanation—both terms for a sophisticated process of drawing inferences.

According to NRCSL Associate Director James Voss, argument, too, is an inferential process by which the principles, facts, and conclusions of a given discipline are supported. The grounds for judging whether arguments are sound are the discipline's standards for evidence. In social science and other "ill structured" disciplines, says Voss, assertions and conclusions are often based on beliefs and supported by informal, or everyday, reasoning. Voss studies the construction, evaluation, and justification of informal arguments in such fields in an effort to develop an empirical understanding of informal reasoning and to determine the best ways for cultivating it in the classroom.

In social and political science, arguments are as ubiquitous as texts, arising whenever more than one interpretation of a fact or phenomenon is possible. Also like texts, arguments are necessarily incomplete, leaving implicit much of the knowledge and reasoning from which they are constructed. Thus, fully grasping an argument may require as much close, inferential processing of its content as comprehending a text does. In this sense, argumentation is as much a form of reasoning as reading is, whether one is evaluating someone else's argument or constructing and justifying one's own.

"Most children, even by the end of middle school, are very ill-prepared to construct, understand, or assess arguments."

Because reading, writing, arguing, and reasoning are so tightly intertwined in learning, it would be reasonable to expect that the skills and structures of argumentation would receive a great deal of attention in schools. Voss, however, says, "Most children, even by the end of middle school, are very ill-prepared to construct, understand, or assess arguments. They can't pick out the major points of an argument. Very few can write an argument-based paragraph. They don't know the components of arguments—premises, conclusions, counterexamples—because these aren't taught in school."

An inspection of elementary history texts conducted by a doctoral candidate working with Voss showed, for example, that the texts "tend to be written like narratives, and in the narratives there is not much causal explanation or justification--just, one thing happened, and it might have caused something else—but there's very little analysis of the events and motivations." In addition, this line of research showed, in studies that asked 5th-, 7th-, 9th-, and 11th-grade students to respond to questions requiring informal reasoning, that students with the highest general ability levels did better than those of average or lower ability. Surprisingly, though, says Voss, "Kids in 11th grade were not doing better than kids in 5th grade. In fact, the high-ability 5th graders were doing better than the mid- to low-ability 11th graders." This lack of improvement in informal reasoning from grade to grade is a consequence, in Voss's view, of the fact that schools do not teach the skills or components of argumentation.

Nevertheless, Voss points out, research has shown that children can generate effective arguments, outside school, in situations that are important to them. They can skillfully persuade parents to grant privileges or convince friends to concede a point of view, presumably because they have mustered the necessary information to bolster their position. "But ask those same kids to construct an argument in history, and they can't do it," Voss says. "If you add some instruction in argument along with the history content," he suggests, "that might change." Because Voss believes schools and texts should build on children's demonstrated ability to argue by explicitly teaching argumentation and causal analysis, he has conducted empirical investigations into the nature of informal reasoning in social science issues. In particular, he has examined the process of argument generation in social controversies such as those surrounding gun control, abortion, the death penalty, and testing for AIDS or for drug use. This work is based on earlier studies of the inferential processes by which people build mental representations of a problem in order to reason about it. The work on argument emphasizes the components of those inferential processes rather than the construction of mental representations.

For example, Voss says, "To understand something in social science, such as a historical event, learners need to analyze it, reconstruct it, put the pieces in order and in the right relation to each other. In order to do that, they need background knowledge, the skills that allow them to apply and connect that knowledge, and the ability to access information as they need it—in other words, to retrieve their background knowledge from memory." Argument construction is one mechanism for analyzing a social science concept or event, and in this case, as Voss explains, "How people generate, justify, evaluate and recall arguments has impact on their ability to think and communicate about topics in a subject area."

"How people generate, justify, evaluate and recall arguments has impact on their ability to think and communicate about topics in a subject area."

Voss began working with college students to examine these processes, asking them to generate as many pro and con arguments as they could in regard to various stated positions on controversial issues. Most people generated very few—a finding that Voss attributes to "output interference," or the fact that accessing memory for information in support of some arguments seems to inhibit further searchers for more information—but of those few, more tended to be in support of the students' personal views than in opposition to them. Even with the aid of cues (rather like the high-level prompts given in Chi's studies), subjects generated only one or two additional arguments. Thus, according to Voss, if a given study involved 40 people, they might collectively generate only about 15 pro and 15 con arguments; and a single individual might come up with only three of the 15 that supported his personal view and only one or two of the 15 that opposed it.

Moreover, Voss adds, if those same 40 people were asked to return 2 weeks later and repeat the same exercise—generating arguments for and against the same proposition—they would repeat only about one-third of their original arguments. All the other arguments offered in the second session would be new ones, which in Voss's view suggests that these "argument structures," or mental representations, "are not very stable and that the arguments that are repeated are the ones that the person holds as being stronger." Voss believes, "People tend to have a few arguments in mind that they associate with a given issue, and they probably generate the rest pretty much on the spot. The fact that they don't generate very many and that most of them are not stable suggests that they have relatively few ideas—not very much information—about the issue."

Knowledge can compensate somewhat for lack of skill.

From these studies, Voss concludes about argument generation what Perfetti concludes about reading—that background knowledge plays a greater role than skill, as important as skill has also been shown to be. The fact that children can generate persuasive arguments with parents or friends, even without being taught the structure and components of argument, suggests that, as in reading, knowledge can compensate somewhat for lack of skill. This suggestion is further supported by the finding that people tend to generate most of their arguments in support of their own beliefs, which Voss believes is because they have more background knowledge that upholds their opinions.

Nevertheless, Voss maintains, it is necessary for schools to provide instruction in the skills of argument, and to encourage students to practice them frequently, so that the content already covered by the curriculum can combine with skill to support true reasoning. Voss's newer work, therefore, is a joint effort with NRCSL's John Levine to study ways in which group processes influence the development of informal reasoning skills, the kinds of training or experience that could facilitate reasoning in the classroom, and the extent to which social science instruction should place more emphasis on causal explanations and justifications.

Argument and Changes in Thinking

The alliance between Voss and Levine is a natural outgrowth not only of Voss's inquiries into the nature of informal reasoning and argument but also of Levine's work on the cognitive impact that argumentation in small groups can have upon the thinking of individual group members. Two complementary strands of this work—one dealing with the effects of anticipated group disagreement and one with disagreement in actual groups—investigated whether, and to what extent, cognitive conflict can motivate and promote learning. Questions underlying the research included: How do discussions among people who agree on an issue differ from discussions among people who disagree? Do lively disagreements yield a more sophisticated understanding of a topic than discussions that lack challenges and counterexamples? Do participants have different cognitive representations of argumentative discussions than of agreeable ones? What are the cognitive effects of being (or expecting to be) a minority opinion holder as compared with a majority opinion holder?

In Levine's studies of actual, as opposed to anticipated, disagreements, he assigned college students to three-person groups that were divided two-to-one over a controversial social issue such as the death penalty, the insanity defense, or prayer in the schools. Group members discussed the issue and then recorded their opinions and the number of arguments they could remember from the discussion. In some groups, the minority member succeeded in changing the opinion of at least one majority member; in others the majority changed the minority member's position; and in some all members maintained their original views on the topic. Levine was particularly interested in the dynamics of the groups in which cognitive changes took place, and in the nature of those changes. As he explains, "they have relevance to teaching and learning. It is of interest, from an instructional perspective, to learn whether students reason differently, and whether they are better arguers, under some circumstances than under others."

Analyses of data taken from the small-group studies showed systematic differences between groups depending on whether the minority or the majority influence was stronger. For example, minority members who either succeeded in changing at least one majority member's opinion or at minimum refused to change their own view were the most talkative and active members of their groups. "They made many assertions about facts," says Levine. "They didn't ask many questions. They were very self-confident." The opposite was true of minority members who, says Levine, "caved in" to the majority and changed their minds. These minority members talked less, were less assertive, and showed less confidence.

Other cognitive differences showed up in the participants' ability to remember the arguments of other group members. Majority members recalled minority arguments when those arguments held firm against their own or succeeded in changing their own; that is, when the minority arguments were actively and assertively expressed. Majority members failed to remember minority arguments when the minority member changed his opinion; that is, when the minority arguments were weakly expressed. On the other hand, minority members *did not* remember majority arguments that convinced them to change their opinions.

According to Levine, such patterns of recall and assertiveness suggest that simply assigning students to classroom discussion groups may not be as productive as trying to design those groups for certain outcomes. "Discussion groups can end up operating in different ways," Levine says. "And those different ways can have important differences for students learning to think. Clearly, a strong, consistent minority can have an impact on what happens with the majority. But when a minority member is persuaded to change his mind, it seems not to be because the majority is so strong or assertive—more likely it is because he has felt intimidated."

In the studies involving anticipated conflict, Levine wanted to know how the prospect of participating in a group argument would affect cognitive activity. "How hard will you work if you think you are going to be in a group of six in which everyone else disagrees with you? What about a group that's divided three to three? Four to two? Do your opinions change? Do you look for arguments to bolster them? Do you research the opposition's arguments?" Researchers asked the college students who took part in this study how much pressure they thought the group would put on them and how likely they thought it was that the other group members would adopt their position. Responses indicated that minority members expected group pressure to correspond inversely to the size of the minority. In other words, a lone minority member expected more pressure than someone who shared the minority view with one or two other members. Similarly, minority members were less likely to expect the group to adopt their view, especially if they were the single proponent of that view.

Levine was particularly interested to see how people's expectations of their role in the group would affect their preparation for the discussion. Would they read only arguments that supported their own position, or would they examine arguments they thought they might meet in their opponents? How long would they spend reading the background materials available to them? The outcomes of the study were systematic in that minority members spent more time reading than majority members, and those who were in one-person minorities looked only for material that supported their position. Those in two-person minorities were more even-handed, reading up on both their own and the opposition's views. Majority members who anticipated strong (two-person) minorities also read only what would bolster their own views, becoming even-handed only if they expected to confront just one minority member. Thus, Levine concludes that when people expect to have to present and defend a position on an issue, their information gathering corresponds to the amount of challenge or pressure they believe they will encounter. The stronger the opposition they anticipate, the more time they will spend on research and the more likely that their research will be biased.

"What this study suggests for instruction," Levine says, "is that the mere anticipation of having to argue a position publicly is strong motivation for activities that foster learning and thinking." Together, the strands of Levine's work indicate that both anticipated and actual discussions about contradictory opinions might prove to be useful instructional techniques in classrooms.

". . . the mere anticipation of having to argue a position publicly is strong motivation for activities that foster learning and thinking."

Thinking Through Experimentation

Concerns of Research: Connections Between Subject Matter and Scientific Discovery

Scientific experimentation offers rich opportunities for looking closely at cognitive processes of learning and instruction. In fact, experimentation mirrors the learning process itself. For example, as students experiment within a science domain, they actively seek and generate evidence, reflect on their theories, evaluate data with respect to those theories, check and monitor changes in their beliefs over time, and sometimes generate new ideas about the way the world works.

Thus, in science, as in any field, the attainment of higher-order thinking and problem-solving skills depends on the learner's ability to forge durable, useful connections between background knowledge and the content of instruction. However, the content of each subject has a characteristic structure determined by its fundamental concepts and principles and the cognitive demands they make on learners. Moreover, in science, it is often possible to view the same phenomenon as illustrative different analytic structures. For example, a student may think about the same electrical circuit as being (1) an example of the technological problem of how to set up the circuit so that two switches in different places can turn a light on or off; (2) an example of Ohm's Law, which specifies the relations among voltage, current, and resistance in the circuit; or (3) a context in which the potential difference across the circuit results in a cumulative motion of charges. Although all three of these analytic "views" are about the same circuit, each view contains different elements and different structural relations among the elements. Thus, as in Chi's research, a major goal of learning research is to understand just how the content of a discipline shapes the thinking of those who study it. Given the different structures that occur both within and across scientific disciplines, are there any generally applicable learning skills, or do the strategies and skills in experimentation and discovery depend entirely on the specific form and content of the topic?

While Chi's work concerns the different kinds of mental representations that apply to different scientific concepts, other work at NRCSL has to do with how the comparative structures of scientific disciplines affect learning, experimentation, and discovery. In order to understand better how instruction can encourage students to become scientific thinkers and problem solvers, this work considers the relations among students' conceptual beliefs, the structure of the subject matter, and the students' strategies for generating and interpreting evidence during experimentation.

How Learning Proceeds in Three Computer Laboratories

To investigate these matters, researchers at NRCSL built three computer laboratories, or microworlds—learning environments that simulate actual phenomena, allowing hands-on investigations of three science subjects: microeconomics (*Smithtown*); electrical circuits (*Voltaville*); and the refraction of light (*Refract*). In each of the microworlds, explains project director Robert Glaser, "Students were asked to take the role of apprentice scientists, to discover as many rules and principles of each topic as possible. They were to do this by designing experiments, interpreting them, and revising their theories in light of the outcomes. In broad terms, the tasks across the three laboratories is the same one. However, the ways in which the task is influenced by the structure of the topic are quite different in different microworlds."

Glaser's research partner, Leona Schauble, explains some of the structural differences among the three subject areas and their effects on students' discovery efforts: "In *Smithtown*, students make qualitative inferences about the relations among variables. The structure of the *Smithtown* microworld is one of covariation—if you change one variable, regular changes may occur in some of the others. Moreover, students have strong expectations about what those relations will be, since they have a lot of experience with buying and selling. Some of these expectations are consonant with the way economic theory describes them, and some are not. The ones that are not are very hard to change because they are so firmly rooted in everyday experience." In *Voltaville*, on the other hand, the form of reasoning is quantitative rather than qualitative. People have had less direct experience with electricity, and their experimentation is therefore less likely to be driven by strong conceptions—either correct or incorrect. The structure of this microworld is a set of underlying rules in the form of mathematical formulae, and the learner's task is to discover these principles by seeking mathematical relations among the variables that they explore. The third computer laboratory, *Refract*, has a mixed structure, sharing features of *Voltaville*'s rule-discovery structure and *Smithtown*'s covariation structure.

In order to learn what kinds of experimentation strategies students would bring to bear in these three different domains, researchers asked twelve college undergraduates to work in all three laboratories over a period of several weeks. In each case, *Refract* was the last microworld the students explored. The purpose of the study was to track students' cumulative learning over all three of the laboratories and to determine which experimentation strategies were general across the three domains and which were particular to one or more domains. Tests administered before and after students' sessions with each laboratory provided a measure of learning. Researchers also made close observations of students' experimentation activities in the laboratories, including their generation and interpretation of evidence anu ..ie ways in which they organized and recorded the information they gathered.

Each computer laboratory presented students with a different number of variables and parameters and, as mentioned above, different structural relations among them. The "problem space," or the total number of unique experiments that could be run in each was different. *Voltaville* supported the smallest problem space, *Smithtown* the largest. Though *Smithtown* has only one major variable—price—it has eight parameters, including income level, population, interest rates, and even weather. A minimum of 50 experiments is required to discover all of *Smithtown*'s laws. In contrast, it takes a minimum of six experiments to discover the laws that apply in *Voltaville* and about 20 in *Refract*. Therefore, the process of discovering relationships and regularities in *Smithtown* is more complex and difficult than in either of the other two laboratories, not only because of its larger problem space but also because it is very easy to confuse parameters with variables.

In general, Glaser and Schauble found that successful students were sensitive to the different structures and complexities of the laboratories and varied their experimentation activities accordingly. Because it is necessary to generate three price values at two or more levels of a parameter to discover many of the principles in *Smithtown*, students changed parameters more often in that microworld than in the others. In contrast, they changed variables more often in *Smithtown* and *Refract* than in *Voltaville*, because laws in those microworlds more often take the form of covariations among variables and outcomes.

Given that successful students tuned their experimentation to the structure of the domain they were working on, the obvious question is what this specificity implies for learning general experimentation skills in science. Rather than a pattern of a set of invariably successful experimentation skills applied across all three domains, the findings revealed that students did not tend to apply the same activities and strategies across all three microworlds. Rather, they applied similar strategies to similar tasks, regardless of which laboratory the tasks appeared in. As Schauble notes, even "a group of students who all have identical scientific reasoning skills may vary considerably in how and when they apply them." The researchers therefore looked closely at the experimentation activities and strategies of the participating students. They found that different students were successful as a function of the different skills required in the various discovery situations, but they also found that all students learned more as they progressed through each of the laboratories in turn. This finding indicates that somehow the strategies being practiced in

"A group of students who all have identical scientific reasoning skills may vary considerably in how and when they apply them."

Smithtown and Voltaville were helping students in their work with Refract. Thus, students were to varying degrees "learning how to learn," and the significant question was to identify the ways in which the better learners developed this ability within the laboratories.

What Glaser and Schauble found, in examini: g the learning of students across all three microworlds, was that those who learned the most about the processes involved in successful scientific experimentation tended to engage in several activities that were different in kind or in quality than those of the less successful learners. In identifying and reporting these activities, the researchers compared the efforts of "Allen," a student who learned efficiently and well, with those of "Joe," whose learning was less successful. Glaser and Schauble analyzed the two students' learning in terms of their search for evidence, their persistence, focus, use of disconfirming feedback, ability to make good use of prior knowledge, and ability to apply relevant heuristics and tools of analysis.

Glaser and Schauble contrasted Allen's behavior to Joe's in regard to all six of these criteria. In his searches for evidence concerning the laws of a given microworld, for example, Allen typically arrived at a tentative hypothesis after only one or two experiments. His further searches were therefore "hypothesis driven"—they represented efforts to confirm his clear expectations about the rules and relationships that characterized the subject area. Joe's experiments were "data driven"—he generated quantities of information without distinguishing between data that could suggest a hypothesis and further data that could support or disconfirm it. He did not seem to design experiments in a patterned or systematic way, and he conducted several that were redundant or served no clear purpose. He generated fewer hypotheses than Allen, and seemed to regard those he did generate as conclusions rather than as statements that needed to be tested against further evidence.

Not surprisingly, Allen also understood better than Joe did when to persist in a line of investigation and when to abandon it as unfruitful, and he pursued his investigations systematically, completing the work related to one law before proceeding to the next. Joe tended to jump around from one line of inquiry to another within a topic, and as a result he made discoveries more slowly and in a more disconnected way.

These qualities of persistence also relate to learners' abilities to focus their attention and to take disconfirming evidence into account in their investigations. For example, Allen was not only better able than Joe to identify and persist in fruitful as opposed to extraneous experiments but was also more likely to think about the microworld problems between sessions and to reorient his attention effectively when he resumed his explorations. He also was more sensitive than Joe to indications that he was pursuing an erroneous hypothesis. When he received computer feedback that disconfirmed his ideas, he was more likely than Joe was to wrestle with his error until he corrected it. Joe, on the other hand, often misread or misinterpreted disconfirming feedback and persisted in unproductive experimentation.

Similarly, Joe was less willing than Allen to let go of mistaken prior knowledge or expectations. In *Smithtown*, for example, he was unable to see the difference between causal and noncausal factors in an observed relationship between price and demand because he regarded his prior expectation of a causal relationship as "proof" rather than as a hypothesis. Allen, however, worked deliberately to resolve discrepancies between his background knowledge and the new information he obtained from running experiments in the laboratories.

Finally, Allen's more generally mindful and attentive approach also made him more likely than Joe to think analytically about problems in the microworlds, to perceive shifts in the patterns formed by interactions between variables and/or parameters, and to apply mathematical or graphical procedures appropriately.

In order to learn how to learn, students must become increasingly sensitive to the differences and similarities among learning tasks in different disciplines.

The general skills Glaser and Schauble identify are, like the skills of self-explanation identified by Chi and the text-processing skills described and modeled by Beck and McKeown, largely self-regulatory. In order to learn how to learn, students apparently must become increasingly sensitive to the differences and similarities among learning tasks in different disciplines. They must also adapt their existing skills accordingly, developing an ability to determine which of their skills are appropriate to which tasks, how to apply them to those tasks, and how to develop further skills as they are needed.

The question for instruction is how to help students develop these self-regulating abilities, and at least part of the answer lies in providing rich opportunities to practice with scientific problem solving in situations that students can manipulate directly. The microworlds are only one kind of environment for such practice, but, as Schauble explains, their hands-on features are particularly effective, especially at demonstrating the true nature of scientific exploration. "There is no point in expecting children to read the scientific method section that starts every science textbook and then expect that they will know how to think about the results of experiments and the meaningfulness of evidence and how to interpret data." Schauble adds that most elementary and intermediate science texts do not teach or discuss thinking skills. In fact, she says, "I think they go overboard in the other direction.... They present strings of disembodied facts; there's little coherent explanation anywhere.... Strings of declarative facts appear to be the norm."

These failings of texts are clearly the basis for many strands of NRCSL work by Perfetti, Beck, McKeown, and Chi. Of Chi's work, in particular, Schauble observes, "It is so complementary to ours that it is almost like the other side of a penny.... She zooms in on smaller episodes of reasoning, how people generate self-explanations when they are reading. We zoom out and say, how does experimentation happen. She zooms in and says, let me compare the structure of knowledge in this biology topic and this physics topic. We zoom out and say, when students are studying in this microeconomics laboratory, what strategies do they use that are different from the strategies that they use in this electrical circuits laboratory. Our concerns are very similar, but we go about them a little differently."

Intelligent Tutoring System Enriches Microworlds

Though Glaser and Schauble's computer microworlds were developed at NRCSL for research purposes—that is, as stimuli for student reasoning and not as teaching tools—their classroom potential is clear from the amount of learning that research subjects were able to achieve with them. This potential has been enhanced by an intelligent computer program called Discovery and Reflection Notation (DARN) that helps students to evaluate their own experimentation strategies as they apply them. As Schauble explains, DARN provides graphical traces of the learner's progress and reasoning in relation to a given experimental strategy that the learner has entered. The program provides three views of the student's experimental activity, and any of the three can be called up by the learner at any point in an experiment or series of experiments.

The first view of a student's experimental progress that DARN provides—the "student view"—is a purely descriptive account of the steps the learner has taken in carrying out her strategy. But it is a high-level description in that it shows her, in an expandable box on the screen, whether her experiments relate to the strategy she has entered, whether she has made predictions, whether they were correct, which data management tools she has used, whether she has made hypotheses, and whether they have been accepted by the computer or she has been asked to do further work.

The second view, the "plan view," shows the logical relation of a series of experiments to the plan the student has entered. It analyzes whether she has followed the plan through to its conclusion or jumped to another plan in mid-path, and its design is intended specifically to foster some of the mindful, self-regulatory skills that account for a persistent and systematic approach to a problem. The third view, the "expert's eye view," also aims to model a kind of self-regulatory skill for students. It keeps track of the data generated by students and—if it detects enough evidence to justify a conclusion they have failed to make—prods them to review their evidence for possible missed connections.

Thus, DARN is one example of an instructional aid that can emerge from the richly specific findings of one line of deep cognitive research. It arose directly from Glaser and Schauble's observations of differences between better and poorer learners, and it represents their attempt to raise the poorer learners' level of mindfulness from a strictly procedural attention to their activities—which loses sight of their general goal—to a level at which they stay focused on planning experiments, making predictions, manipulating variables, and tracking results. These, say Schauble, "are the things that actually have to do with the different *conceptual* pieces of experimentation."

Continuing Investigations

Current Research Projects

Each line of NRCSL research described in this report has posited or helped to confirm and refine some ways in which classroom instruction can help students learn to think and think to learn. Each project has both illuminated the nature of reasoning and learning and raised questions for further investigations that are now under way.

For example, the St. Agnes School project, which developed and implemented discovery-based instruction techniques for the primary grades, is now developing related new teaching methods for the middle grades. This project, now called $Math^3$ (Making Mathematical Meaning), has also generated a new line of theoretical research, a qualitative study of $Math^3$ classrooms that attempts to distinguish the features that actually account for the program's positive impact.

Similarly, projects on text comprehension have taken the findings discussed in this report and have begun to apply them to the enrichment of textual resources in the classroom. Researchers who have investigated basic reading skill as a general learning ability now explore the kinds of reasoning that can be fostered through the use of differing or contradictory texts on the same topics. Such reasoning, now being studied in the context of history learning, may also promote learning in other, similarly structured subjects.

In a related vein, the projects on argumentation and on cognitive conflict within small groups have now converged to study the motivational effects of social, as opposed to textual, controversy. Researchers are examining the classroom use of dialectical interaction as a means of both motivating and sharpening students' reasoning skills.

The text-revision line of work, meanwhile, is engaging both teachers and students in analyzing and revising texts. Researchers feel that this activity may focus readers' inferential processes and nurture the skills that probing and thoughtful readers need in order to get the most out of written material. This project, using a process called "Questioning the Author," suggests that students who learn to identify and correct for textual problems and inadequacies not only gain a deeper understanding of textual content but also refrain from blaming themselves for failed comprehension.

Current NRCSL projects in science learning are likewise broadening earlier work into new research and the development of classroom interventions. One project, which studies the role of explanations in biology learning, is based on findings that when students construct explanations for scientific phenomena they can sometimes overcome difficulty in understanding theoretical concepts. The project will design prototype instructional materials and procedures for assessing students' explanations.

Another science research project expands on the studies of learning in computer laboratories by analyzing and promoting opportunities for reasoning in the science classroom. The researchers focus on how specific classroom activities foster or impede scientific thinking and problem solving. They too are developing instructional interventions that can test emerging theories about science learning under various conditions. These interventions are being developed, piloted, and refined in Pittsburgh public school classrooms.

Finally, classroom-based studies of expert instruction continue to investigate the complex nature of effective teaching. The current work has undertaken a deep analysis of the critical features of teacher explanations that were identified in earlier studies. Researchers are focusing on explanations in geography and their role in student understanding. The project will also work with teachers on the design of effective explanations that take account of subject-matter content and structure.

The Growing Connection Between Research and Practice

The relationship between NRCSL researchers and teacher-collaborators continues to grow. Every research project now under way either conducts classroom-based research, works directly with teachers to develop instructional materials or methods, or is preparing for some form of teacher-researcher collaboration before the end of the current funding period. Teachers also continue their role in the major, ongoing collaborations, *Thinking Mathematics* (now applying for funds to expand its teacher-led development of prototype teaching materials) and the Math^3 project.

NRCSL's expanding connection with practice reflects the advancement of the field of cognitive research. With the formative theory of knowledge construction well established, research has been able to turn increasingly to the development and study of reforms based on that theory. Because successful classroom reforms cannot proceed without addressing realities that only classroom teachers confront and fully understand, collaborations have become indispensable to the work of education research. At NRCSL, therefore, the ultimate aim of research is threefold: to provide a scientific base for education reform; to take the lessons gained from implementation back to the laboratory for further theoretical study; and to attend closely to every issue and question that arises in the intermediate stages of work—the invention, testing, piloting, and refinement of new classroom methods.

ISBN 0-16-041885-2
90000
9 780160 418853

United States
Department of Education
Washington, D.C. 20208-55[illegible]3

Official Business
Penalty for Private Use, $300

Postage and Fees Paid
U.S. Department of Education
Permit No. G-17

FOURTH CLASS BOOK RATE

OR 93-3232

BEST COPY AVAILABLE