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ABSTRACT

Since 1983, the Educational Technology Center at the Harvard Graduate School of Education has studied the uses of computers and other technologies to improve K-12 instruction in science, mathematics, and computing. Collaborative research groups--including scientists and mathematicians, practicing teachers, learning theorists, and software designers--have focused on "targets of difficulty," or curricular topics that are both crucial to students' further progress in these fields and widely recognized as difficult to teach and learn. More than 15 research projects have been completed to study the nature of students' difficulties, clarify the educational advantages that computer technology offers, and design experimental lessons that use computers as well as traditional materials to address these difficult topics. Three research groups tried promising teaching units in five Massachusetts high schools to learn about their use in regular classrooms and schools. This monograph summarizes the results of the Educational Technology Center's work and their implications for policy makers, school practitioners, and others concerned about science and mathematics education. The findings of the research project fall into three categories: (1) teaching and learning; (2) technology; and (3) implementation. (PK)

Making Sense of the Future

A Position Paper on The Role of Technology in Science, Mathematics, and Computing Education

Educational Technology Center
Harvard Graduate School
[illegible]

Educational Technology Center

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Making Sense of the Future

A Position Paper on The Role of Technology in Science, Mathematics, and Computing Education

Educational Technology Center
Harvard Graduate School of Education

January 1988

Contents

The purpose of this essay is to distill for a broad audience of educational practitioners, policymakers, and researchers what ETC has learned in the last four years of research and to present our position on what should happen next in research on educational technologies. Neither a technical report nor a formal proposal with references, data tables, and methodological detail, it is intended to stimulate discussion on this important topic. Further information — including technical reports, software, and teaching materials — is available from ETC.

Summary

Since 1983, the Educational Technology Center has studied the uses of computers and other technologies to improve K-12 instruction in science, mathematics, and computing. Our collaborative research groups — including scientists and mathematicians, practicing teachers, learning theorists, and software designers — have focused on "targets of difficulty," or curricular topics that are both crucial to students' further progress in these fields, *and* widely recognized as difficult to teach and learn. More than fifteen research projects have studied the nature of students' difficulties, clarified the educational advantages that computer technology offers, and designed experimental lessons that use computers as well as traditional materials to address these difficult topics. During the past year, three research groups tried out promising teaching units in five Massachusetts high schools to learn about their use in regular classrooms and schools. This essay summarizes the results of the Educational Technology Center's work and their implications for policy makers, school practitioners, and others concerned about science and mathematics education.

Our main goal has been to develop ways to "teach for understanding," our phrase for approaches that seek not simply to help students memorize vocabulary and algorithms, but rather to help them understand and apply mathematical and scientific reasoning. To do this we have analyzed subject matter and students' ideas about it, using these as the basis for designing teaching methods and materials, and for determining when and how to use technology. The findings of our research projects fall into three categories:

Teaching and Learning. Help students develop a deep understanding of the subjects they study by taking into account their intuitive theories and misconceptions and by integrating directed instruction with opportunities for students to actively explore problems. The teacher's role includes helping students to construct new knowledge through critical analysis of data. Teaching materials and strategies focus on key concepts *and* on the nature of knowledge, evidence, and inquiry in a discipline.

Technology. Use technologies selectively to make a distinct contribution to teaching and learning, for example, to present dynamic visual models of key ideas, to help students gather and display data, to allow them to construct and manipulate screen "objects" such as graphs or geometric figures, and to give teachers and researchers a window on students' thinking and learning.

Implementation. Include school people in all phases of research to help ensure that the resulting technology-enhanced teaching approaches will fit with current curriculum and instruction. The translation of research findings into practice involves cycles of designing and assessing innovative materials and approaches, to make them both educationally powerful and practical in schools. One successful format for achieving these twin aims is a series of research-based lessons designed to be woven into an existing course. These lessons highlight key concepts and strategies so that teachers may readily infuse these elements into other lessons in the course. At ETC we have successfully designed one such metacourse, as we call it, and developed many of the ingredients for several other metacourses.

Metacourses offer an alternative to more traditional curriculum development approaches that tend toward large-scale, whole-course efforts or well-defined, distinct teaching units. They can provide regular courses with a vitamin shot of technology-enhanced assistance both to teaching content and to teaching students how knowledge is made in a particular subject area. Built on research-based educational innovations which, in their prototype form, produced promising effects on student learning, metacourses must include support materials designed to help teachers acquire the knowledge and skills needed to teach the metacourse lessons themselves and to infuse the key elements from these lessons into other parts of their courses.

These findings and implications suggest a program of future research in several areas. First, there must be continued inquiry into the way students think about what we want them to learn. Complementing this investigation must be research on the design of materials that teach both important content and the process of solving problems and constructing knowledge in particular domains. Assessing the impact of such materials on student learning is another subtle but important area of inquiry. Given the goal of teaching for deep understanding, this must include not only traditionally accepted measures of student achievement, but also other measures designed specifically to assess the more complex reasoning abilities promoted by new teaching interventions and to trace other subtle effects, such as changes in teacher behavior, changes in classroom interactions, and longitudinal changes in students' pursuit of further study. Research must also identify the materials, resources, and supports that will help teachers in regular school settings to use new technologies and to guide students' inquiry effectively.

Introduction

For four years the Educational Technology Center (ETC) has studied the uses of computers and other technologies to improve elementary and secondary instruction in science, mathematics, and computing. Within these areas, collaborative research groups have focused on "targets of difficulty," or topics that are both central to the curriculum and widely recognized as difficult to learn. They have studied the nature of students' difficulties, clarified the educational advantages that computer technology offers, and designed experimental lessons that use computers as well as traditional materials to address these difficult topics. During the past year, three research groups tried out promising teaching units in five Massachusetts high schools to learn about their use in regular classrooms and schools.

Our research groups have focused on "targets of difficulty," or curricular topics that are crucial to students' further progress in these fields, yet difficult to teach and learn.

We began our work knowing that the last decade of research in science, mathematics, and computing had shown that many students finish high school without understanding the concepts they have encountered in the classroom — even when they can pass information-based tests and solve conventional textbook problems. Recently, science and mathematics educators, researchers, and policy makers have united in calling for efforts not simply to help students memorize vocabulary and algorithms, but to help them understand and use mathematical and scientific reasoning. At ETC, our primary goal is to develop ways to "teach for understanding," our phrase for an enlarged concept of basic education that includes deep exploration of key ideas, an improved ability to identify and solve problems, and an overall grasp of the nature of science and mathematics.

Of course, no one is likely to argue against this effort; all educators want understanding. Yet achieving this goal is a subtle and challenging enterprise in ways just becoming clear from research in cognitive science and in the disciplines. This research reveals that students bring to the classroom both considerable knowledge and resilient misconceptions about scientific and mathematical phenomena, and it recommends that education begin with students' notions. At ETC we analyze subject matter and students' ideas about it, using them as the basis for designing methods of teaching for understanding and for determining when and how to use technology. To attend to all these elements at once and to help ensure that our findings will be applicable to classroom practice, ETC research projects bring together cognitive psychologists, mathematicians and scientists, designers of educational media, and experienced schoolteachers and curriculum developers.

We have adopted the phrase "teaching for understanding" to stand for an enlarged concept of basic education that includes deep exploration of key concepts, an improved ability to identify and solve problems, and an overall grasp of the nature of science and mathematics.

The work of more than fifteen projects over four years has yielded four principles for teaching science and mathematics with new technologies:

(1) **Goals:** Focus on key concepts *and* on the overall nature of knowledge, evidence, and inquiry in a discipline.
(2) **Teaching Approaches:** Help students develop a deep understanding of the subjects they study by taking into account their prior theories and by integrating teacher-directed instruction with opportunities and challenges for critical inquiry.
(3) **Technology:** Use technologies selectively to make a distinct contribution to teaching and learning, for example, to present dynamic models of key ideas or to enable students to participate in disciplined inquiry.
(4) **Implementation:** Design technology-enhanced teaching modules and

approaches that can be gradually and gracefully integrated into existing curriculum and practice.

To attend to all these elements at once and to ensure that our findings will be applicable to classroom practice, ETC research projects bring together cognitive psychologists, mathematicians and scientists, designers of educational media, and experienced schoolteachers and curriculum developers.

These principles inform our thinking about educational productivity and educational improvement. Computer technology, like any other educational tool, can be used to further educational productivity in several ways. It can help teachers do a better job of introducing and reviewing basic information, thus increasing the efficiency of traditional instruction, and indeed, many efforts, both publicly and privately supported, now pursue this goal. In contrast, the work of ETC is motivated by the potential of technology to provide powerful interactive learning environments and to present dynamic visual representations that can help students construct their own mental models of abstract or inaccessible concepts and phenomena. By promoting deeper understanding through active inquiry, this way of using technology expands the meaning of "educational productivity."

We believe the educational goals of imparting basic knowledge and teaching for understanding are inseparable. All youngsters must learn, for example, to read and write, multiply and divide, learn that all matter is composed of atoms and molecules, when the Civil War took place, and where to locate Chicago and Paris on a map. At the same time, to make such knowledge work for themselves and for their communities and nation, students must understand how to pose problems, conduct critical inquiry, and develop informed insight. They must know how to produce and criticize a reasoned written argument, know when and why to multiply or divide, understand what compels the adoption of an atomic theory of matter, understand the events that led to and flowed from the Civil War, and be able to analyze the factors that determine where cities spring up and prosper.

ETC is developing ways of using technology to further these larger educational goals. We have also learned a great deal about how to ensure that the materials and approaches we have developed can be gradually integrated into the policies and practices of real schools. The remainder of this essay explains our work and its implications in more detail. It begins with a review of ETC's goals, approach, and activities. The next section explains findings that have emerged from the Center's research and illustrates them with brief descriptions of particular projects. Finally we outline our recommendations for further research to take advantage of these promising findings.

ETC Goals, Approach, and Activities

As we interpreted the Center's mandate, it encompassed three goals:

(1) to study ways to improve education in science, mathematics, and computing;
(2) to clarify the contribution of information technologies to improved education in these areas;
(3) to make the results of the Center's work easily applicable to classroom practice.

Our approach to accomplishing these goals was based on three premises:

(1) The computer is a tool, not the main focus of our attention. Our primary concern is research on the teaching and learning of particular subject matters, through the use of software, curriculum, teaching strategies, and related materials that take advantage of the educational potential of computers.
(2) ETC research projects concentrate on particular topics in science, mathematics, and computing for two reasons. First, because resources are never sufficient to work on the elementary and secondary curriculum in a comprehensive way, we sought to maximize the impact of the Center's activities by choosing targets of difficulty, that is, topics already recognized by scientists and mathematicians as crucial to students' further progress *and* simultaneously recognized by teachers as important but difficult topics to teach and learn. Second, we believed that insights into the value of new technologies should emerge from analysis of the teaching and learning of particular topics, rather than from broad generalizations that might overlook subtle differences in subject matter.
(3) The history of education reform is filled with efforts that foundered partly because academics told practitioners how things should be done in schools. To avoid adding to that list of failures, we incorporated practicing teachers and operating school systems in every phase of ETC's activities.

These premises led us to structure ETC as a consortium that reflects and supports a commitment to collaborative research. Based at the Harvard Graduate School of Education, the Center includes the public schools of Cambridge, Newton, Ware, and Watertown, Massachusetts; Education Collaborative for Greater Boston; Education Development Center; Educational Testing Service; and WGBH Educational Foundation. The combined expertise of these organizations — in subject matter, cognitive psychology, teaching, curriculum, and educational media — helps assure that the Center's research is not only theoretically and educationally powerful but also readily applicable to classroom practice.

During the past four years, these collaborative research projects have studied the teaching and learning of topics in science, mathematics, and computing and the potential contribution of new technologies to education in these areas (see the Appendix for a list of key projects and products). Each project has been concerned with five issues:

- **Subject Matter.** ETC projects concentrate first on getting the intellectual story line straight. Insufficient attention to the nuance of a topic can cripple or impoverish even well-intentioned instructional efforts. Our projects clarify key concepts and use scientifically and mathematically accurate, although simplified, models (of heat as distinct from temperature, for example, or density or ratio quantities) to help students build a foundation for understanding a discipline.
- **Students' Ideas and Misconceptions.** Next, the projects study how learners learn the subject matter. They review existing information and sometimes conduct further research on students' intuitive ideas and on the misconceptions that lead them astray.
- **Teaching for Understanding.** Throughout the process of designing experimental teaching units, the projects test their materials with students and revise them on the basis of their findings. Test settings become increasingly realistic as the units are refined. Initial research often involves clinical interviews with individual students, while later teaching experiments are carried out with whole classes.
- **Technology.** ETC projects incorporate computers and other new technologies into experimental teaching units to take advantage of the unique capabilities of well-designed software.
- **Implementation.** Throughout their work, projects consider the constraints and rewards that affect classroom teachers and schools as organizations. In devising our technology based teaching approaches we emphasize the use of computer technologies that schools can now or soon will be able to obtain, and we limit our research on technologies that are too expensive to be widely used in schools in the near future. We hope to learn what forms ETC-developed innovations take in practice, and what resources and supports they require to work effectively.

Findings and Implications

ETC's findings fall into three categories:

(1) findings about methods of teaching for understanding;
(2) findings about when and how technology can make a distinct contribution; and
(3) findings about how to ensure that research results are applicable to classroom practice.

In this section we present highlights from the results that have emerged across projects. We have illustrated these general cross-cutting findings with examples from particular projects.

Teaching for Understanding

ETC has worked to tease out and address the components of "understanding" of scientific and mathematical phenomena. At its best, teaching for understanding must foster knowledge of the phenomena being studied, of the key concepts useful in analyzing these phenomena, of the current scientific and mathematical explanations of them, and of the relationships among data, concepts, and explanatory schemes within the relevant subject areas. To help students achieve this kind of understanding, ETC projects have developed a teaching approach with several distinctive elements.

Taking Account of Students' Prior Conceptions

ETC science projects devoted a particularly large amount of attention to the careful mapping of students' intuitive ideas.

Rather than stress memorization of facts and rules, ETC research groups seek to foster mathematical and scientific understanding by helping students revise their prior ideas.

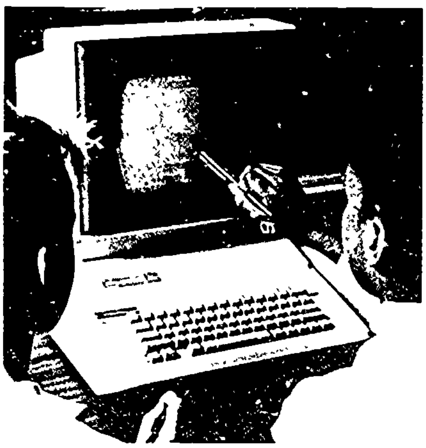
Students come to the math classroom and the science lab with notions about scientific and mathematical phenomena that they have formed from everyday experience and previous instruction. When they encounter new data or phenomena, they can either append them to their prior ideas and theories without integrating the two — and thus achieve a superficial and perishable familiarity with the new material — or they can transform their naive understandings into more sophisticated and lasting ones. Rather than stress memorization of facts and rules, ETC research groups have fostered mathematical and scientific understanding by helping students revise their prior ideas.

ETC's science projects have devoted a particularly large amount of attention during the early stages of their research to the mapping of students' intuitive ideas about their targets of difficulty. The Heat/Temperature Project aims to help students differentiate heat from temperature, a distinction that forms the foundation for understanding the concept of energy transfer as it recurs throughout the secondary science curriculum. This research group found, for example, that most students entering ninth grade science did not understand the concept of amount of heat and lacked a clear grasp of thermal equilibrium. These students' naive, undifferentiated understanding of heat and temperature was, nevertheless, quite coherent and was supported by many everyday experiences and common usage of the terms *heat* and *temperature*.

Almost universally, traditional instruction presents the concepts of heat and temperature through definitions (for example, of a calorie as a unit of heat) and through the laws that relate heat and temperature, including the roles of specific heat and latent heat. The group's first teaching intervention drew on this tradition and used computer software and peripheral equipment

to allow students to deliver fixed amounts of heat to a liquid and to see the resultant change in temperature graphically displayed on the computer screen. The real laboratory was further expanded by laboratory simulations of similar experiments. The lessons in this unit helped students solve quantitative problems about mass, heat, and temperature, and conveyed something of the concept of amount of heat. Like the standard curriculum, however, this intervention did not lead to a full differentiation of heat and temperature. Researchers suspected that the problem lay in the inductive instructional approach which did not explicitly teach students what heat and temperature are. This analysis suggested that students might also benefit from a dynamic visual model depicting heat flow as molecular kinetic energy transferred from a hotter substance to a colder one. The group has developed software of this sort, and preliminary analyses of more recent tests suggest that its visual imagery helps students grasp how heat affects temperature and adds meaning to the activities presented in the earlier intervention.

Integrating Directed Instruction and Inquiry Learning



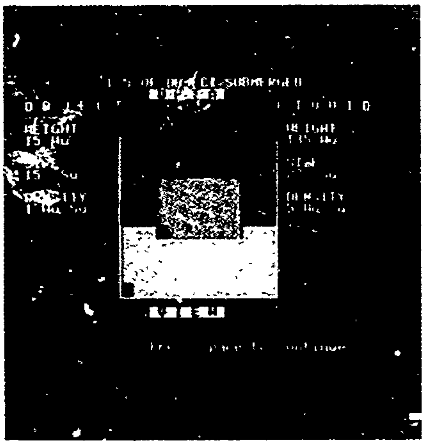
Just as extremely open-ended learning environments rarely lead students to reconstruct concepts that mathematicians and scientists needed centuries to devise, purely teacher-directed or computer-directed learning environments seldom convey those concepts with real understanding. Nevertheless, each way of teaching and learning has important strengths, and ETC has developed a hybrid approach that combines some directed instruction with some episodes of inquiry in which teachers help students develop and test their own ideas. While the mixture of instruction, guidance, and inquiry depends on the subject matter and the needs of students, the aim is to give students some intellectual elbow room but not so much they get lost.

In developing ways to teach students another difficult conceptual distinction, the ETC Weight/Density Project has arrived at an effective blend of guidance and inquiry, both in computer-based activities and in lessons with real materials. Like the Heat/Temperature Project, this research group began by analyzing students' beginning conceptions. Although most middle school students do not know what *density* means, researchers learned that they do have related ideas about "heaviness for size" and what makes some objects sink or float. Most youngsters have one concept (an undifferentiated weight/density concept), where physicists require two. The distinction physicists make is hard to teach because an object's density, unlike its weight, is not directly observable. Students must infer density from what they know about weight and size — an inference that escapes many sixth and seventh graders, despite careful teacher explanations and hands-on activities.

Our hybrid approach combines some direct instruction with episodes of inquiry in which teachers help students develop and test their own ideas.

The Weight/Density Project, like the Heat/Temperature Project, has explored the use of computer-implemented interactive models to help students achieve conceptual change in science. The model this group developed makes density directly observable. It allows students to choose among several kinds of materials, each of a different density, and to build objects of different sizes. The computer depicts each object as a rectangular array of square units. An object's size is shown by the total number of square units it comprises, and its density, not visually apparent with real objects, is shown by dots within each square unit of size — denser materials have more dots per square unit. Finally, the object's weight is depicted by the total number of dots within its boundaries. By limiting the screen display to only the relevant variables, the

Teachers pose problems and guide students to help them make connections between their experience with real materials and the computer representations.



"*This is more parallel to the way I learn. I like learning from experience or from seeing what other people have done. You're doing the stuff yourself so you're rediscovering stuff. It's really your own learning.*" — *Student*

simulation structures the environment. Yet within these planned constraints, students have considerable freedom to explore. The lessons designed by this group use the simulation in conjunction with hands-on activities with objects of different weights, sizes, and densities. Teachers pose problems – about floating and sinking, for example – and guide students to help them make connections between their experiences with real materials and the computer representation, which is in some respects more abstract and in others more concrete.

Findings from the Weight/Density Group's research indicate that their teaching units help students advance along a predictable progression from an initial concept that combines features of both weight and density, to more differentiated but still fragile concepts, to a firm grasp of the distinction.

Teaching How Knowledge is Made

The Nature of Science Project has sought ways to teach students the process skills used in the construction of scientific knowledge. This project has concentrated on junior high students' understanding of the nature of the scientific enterprise – the *how* and *why* of scientific work – within the context of specific scientific phenomena.

In a detailed study of students' entering conceptions about science and scientific investigation, this group found that many junior high school students hold a narrow view of the scientific enterprise: scientists use special equipment and do experiments which lead directly to useful inventions and cures. Most students have no notion of science as the intellectual construction of theories. According to a review the project conducted, the students' limited perspective is supported by current junior high textbooks and standard units on the scientific method. Perhaps as a result, most students do not recognize experiments as tests of ideas (rather than tests of objects to see whether they work), do not understand the importance of searching for contradictory evidence, and do not differentiate hypotheses or experiments from results.

The project's month-long instructional unit is designed to replace a standard unit on the scientific method. Rather than focus only on how to carry out controlled laboratory experiments, the ETC unit asks students to reflect on the thinking that takes place before, during, and after experimentation and on the role of controlled experimentation in the development of scientific ideas. This emphasis helps students to see the relationship between a given problem and their own experience and to understand that doing science is a mental activity.

The unit poses problems to motivate inquiry. Students spend one week investigating several "black box" problems, one of which may be explored in conjunction with the ETC-produced interactive videodisc, *Seeing the Unseen.* During the second week, they examine their implicit knowledge about language and construct explanations of particular language phenomena. For the final two weeks of the unit they investigate whether yeast is a living organism. Each of these activities engages students in theory building and stimulates conceptual change through sustained inquiry into a phenomenon.

Students and teachers have proved enthusiastic about the unit. Most important, it has helped students move away from their initially narrow view of science to see that scientific work originates in the mind of the scientist — not in a laboratory — and that it involves persistent examination of ideas.

Teaching students about the nature of evidence and the process of reasoning in a domain helps them see the relation between models and real world phenomena and fosters understanding of the way people construct and represent scientific knowledge.

Seventh graders taught with this unit tended to learn the mechanics of scientific methodology as well as their classmates who followed a standard unit, *and* they learned more about the nature and purpose of scientific inquiry.

While this attention to teaching students about the nature of evidence and the process of reasoning within a domain is the primary emphasis of the Nature of Science Project, it is an explicit goal in most other ETC research projects as well. The Weight/Density and Heat/Temperature Units both examine the purpose of scientific models, the revisability of models, and the possibility of alternative models for the same phenomenon. Discussion of these issues helps students see the relation between models and real-world phenomena and fosters understanding of the way people construct and represent scientific knowledge.

Using New Technologies to Make a Distinct Contribution

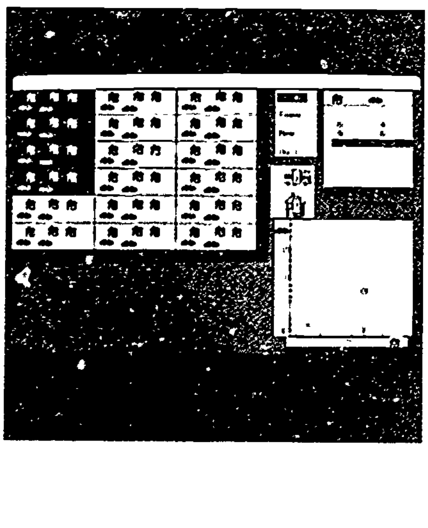
"Things that would be over the heads of the kids and would be saved for a college course in many cases can be done, very simply sometimes, with a computer." — *Teacher*

From the beginning ETC has assumed that new technologies should be adopted not for their own sake, but rather when they offer clear advantages over traditional educational materials or when they make it possible to introduce ideas into the curriculum earlier and more effectively. As a result, we have pressed to discover when and how computers can make a distinct contribution to students' learning. We consider the representational and computational capabilities discussed in this section to be characteristic of current interactive technologies in general, and we believe that future hardware and software developments will take these capabilities to new levels of sophistication and effectiveness.

Linking Multiple Representations

Thoughtfully designed computer software can present multiple, dynamically linked representations in ways that are impossible with static, inert media such as books and chalkboards.

Some of the most fruitful applications of computer technology derive from its capacity to present educationally powerful, dynamic visual images. This is particularly true in science and mathematics, where knowledge can be represented in many ways. Representational flexibility is important for two reasons. First, different representations of a complex idea (for example, a ratio, an algebraic function, or a concept such as heat) emphasize different aspects of the idea and afford different sorts of analyses. For instance, symbolic equations represent algebraic functions most usefully for some analyses, whereas the graphical representations are better suited for others. Understanding the strengths and weaknesses of various representations and the relationships among them helps mathematicians and scientists select and apply them efficiently in solving problems. Second, students differ in their ability to understand and use particular representations. Having several representations available allows a better match between students and the subject matter. Thoughtfully designed computer software can present multiple, dynamically linked representations in ways that are impossible with static, inert media such as books and chalkboards.



The ETC Word Problems Project exploits the computer's representational capacity to help students master one of the trickiest aspects of quantitative reasoning — that involving "per quantities" such as rates and ratios. The project's review of previous research and its initial investigations of student difficulties pointed to particular confusion with word problems involving quantities such as miles per hour or cookies per child. Faced with such problems, students often think that the per quantity — say, three cookies for every two children in the class — tells them something about the particular numbers of cookies and children, when in fact the key is the *relationship* between the two. In effect, the two parts of a per quantity form a third quantity, known mathematically as an intensive quantity. Not only are these quantities difficult to grasp, but their arithmetic is often counter-intuitive.

"You become more organized in your mind after doing all this stuff. Things start to come in columns in your head. If somebody tells you something, you have a bunch of ideas in your head. Not just two, but a bunch of them, and you just kind of sort them through. You're thinking, 'what could be the reason for this?'" — Student

To help students understand and compute with intensive quantities, the Word Problems Project has designed a series of software environments that use four types of visual representations. In the situation of three cookies for every two children, for example, the most concrete representation shows a series of cells, each picturing three cookies and two children. A second representation consists of paired numbers in a table of data, where the number of cookies appears in one column and the corresponding number of children appears in the other. The third representation is a coordinate graph which shows the number of cookies along one axis and the number of children along the other. The per quantity appears on the graph as the slope of a line connecting plotted points. A fourth, more formal representation uses algebraic equations. Still under development, these software environments harness the computer's ability to display any or all of these representations at once and to link them so changes made in one can be viewed simultaneously in any of the others.

The Word Problems Project has devised lessons for fourth to sixth graders that use this software as a "learning ramp" to help students move from the easily grasped iconic representation to the more difficult and mathematically more powerful graph. Using the software environment, ETC researchers have observed progress in ratio and proportional reasoning among youngsters who have failed with more traditional methods. The results suggest that lessons based on such software could be used across as many as five grade levels, opening the way to greater continuity in the K-12 mathematics curriculum and to easier coverage of important ideas.

The ETC Systems Thinking Group, based at Educational Testing Service, also uses multiple representations to teach scientific reasoning. This group is studying the use in high school classrooms of the STELLA software package, which allows students to create graphic models of dynamic systems — population systems or ecological systems, for example — and to observe changes in them over simulated time, as displayed on the computer. The group will assess gains in both systems thinking and content knowledge in courses where the systems thinking approach and STELLA have been used.

Extending the Range of Manipulable Objects

The idea that students can build understanding by constructing and manipulating objects — blocks, Cuisenaire rods, laboratory equipment, and so on — is an old and fertile one. Such materials can help make abstract ideas more tangible. In the classroom, however, teachers sometimes find real-world objects hard to manage and limited in their application. Computers equipped with appropriate software can help overcome these limitations by extending the range of manipulable objects to include the intangible. By permitting students to build and manipulate objects that are otherwise impossible or impractical to use in schools, new technologies enable a teaching approach that has been espoused for decades but drastically curtailed by real-world constraints.

Computers equipped with appropriate software can permit students to build and manipulate educationally powerful "objects" that are otherwise impossible or impractical in the classroom.

The Geometry Project is one of several ETC projects that apply technology in this way. This group has explored the potential of software entitled the *Geometric Supposer* to allow students to work with geometric data as a

"You have to get a conjecture out of nowhere. You have to start it all on your own. The teacher gives us a little something, but we have to come up with most everything. We're not complaining. It's just a little hard sometimes. Maybe we are complaining."
— *Student*

way of learning plane geometry. With the *Supposer* students can make quick, accurate constructions and measurements on any triangle, quadrilateral, or circle. The software "remembers" these constructions and measurements as procedures and allows students to repeat them on any other shape of the same class. Students can generate many constructions, make conjectures about the patterns they observe, and then test their conjectures. They go on to examine what distinguishes interesting conjectures from weak ones and to build important geometric ideas by proving their conjectures.

As a tool, the *Supposer* facilitates accurate and efficient constructions and approximate measurement of those constructions. Even more important, students can "replay" their constructions on other geometric objects, exploring patterns and commonalities across particular instances and forming conjectures about what may be true in general. Like the software developed by the Word Problems Project, the *Supposer* guides students from concrete conceptualizations to more abstract, more general, and mathematically more powerful ones.

Geometry students taught in traditional ways rarely understand why formal proof is necessary. Skeptics about the *Supposer's* empirical approach feared that it would leave students bound by their data and unsure about the purpose or need for proof. ETC's results suggest otherwise: when students enter the subject matter at a level where they can manipulate diagrams, then generalize and confirm their knowledge at a more abstract level, they learn to recognize the limitations of empirical validity and the necessity for logical proof. ETC studies comparing *Supposer*-using classes with traditional geometry classes show that on tests of their ability to provide arguments and to make conjectures, students who used the *Supposer* were far more likely than those in traditional classes to make conjectures about large sets of cases and to provide formal proofs. Although this ability to generalize from data and to think inductively is seldom practiced in traditional mathematics classes, it is a fundamental aspect of mathematical reasoning.

This ability to build broad generalizations from given data, though seldom practiced in traditional mathematics classes, is fundamental to mathematical reasoning.

In addition to research on the impact of the *Supposer* on student learning, ETC researchers have studied the way teachers in five secondary schools carried out this approach in their classes. These teachers reported that students who used the *Supposer* became more facile at manipulating graphical representations of abstract ideas. While using the inductive approach was a major challenge to the teachers and students, they found it a more interesting and enjoyable way to teach and learn mathematics. Indeed, using the *Supposer* changed teachers' thinking about their subject matter and how it might be taught. Several claimed that this innovation boosted their professional morale and their active involvement in mathematics.

Using Software to Reveal Students' Thinking

In addition to using software to teach important concepts and ways of reasoning, ETC researchers and teachers find that appropriately designed software becomes a powerful window through which to observe the way students think and learn. The Algebra Project uses the computer to display multiple, linked representations — in this case, equations and graphs of algebraic functions. The group is currently studying the way students learn to see relationships between those representations as well as the kind of computer-based and teacher-provided guidance that will help them understand what they are observing.

ETC research projects also use computer technology as a window through which researchers and teachers can observe the way students think and learn.

"I learn a lot more about my students because I can watch them learn. Before, when I was in the teacher-centered mode, I couldn't watch them learn because I was busy delivering the curriculum. So my role has changed that way with computers." — Teacher

Linking symbolic mathematical expressions with their graphical representations is a current trend in software development. When the Algebra Project began to study the effects of this genre of software on student learning, researchers noted that students often misinterpreted the graphs of functions and that these misinterpretations sometimes led to incorrect inferences about the relationship between graphs and functions. Because the inability to interpret graphic information is a major impediment to learning much of mathematics and science, the Algebra Project embarked on a study of how students develop this visual perceptual ability. Using software under development at Education Development Center, along with traditional materials, researchers probe students' thinking as they explore the relationships between graphs and polynomial functions expressed as symbolic equations or inequalities. The software allows students to manipulate the parameters of functions expressed symbolically and to observe immediately the effect on the function's graphic representation. Conversely, it lets them alter the graphic representation and observe immediately the effect on the function's symbolic representation. By pursuing this line of inquiry, ETC researchers have learned that students attempting to interpret graphs are often confused by scale. The project is now studying how teachers might pose problems in this software environment to help students overcome such confusions in interpreting the graphic representations of algebraic functions.

Making Research Applicable to Practice

One of ETC's fundamental goals has been to assure that its research would lead to the improvement of educational practice. Our commitment to this goal led us to include four school systems in the ETC consortium and to include experienced teachers in every research group. The views of school people inform every stage of the Center's work so that our research addresses their central concerns, our findings are interpreted in light of their experience, and our lessons are designed to be compatible with their values and to blend readily with existing instruction. While such practical considerations in research design are restrictive at times, we see this approach as necessary for research to affect practice. Our experience has helped us clarify some of the problems, possible solutions, and opportunities associated with collaborative research.

Bridging the Cultures of Schools and Universities to Link Research and Practice

Despite overlapping interests, the relationships between schools and universities have often been fraught with misunderstanding and disappointment. As a result, doing collaborative research requires not merely building bridges where few exist, but also helping people from two different cultures to understand each other's goals, develop a shared language, and work together to see that both research and practice are improved when the two are closely connected.

When ETC was established, we built structural bridges between schools and the Center's research organizations. Each of the four school systems in the ETC consortium was bound to the Center by a subcontract with a specified scope of work and a budget. The district superintendents joined ETC's Agenda Group, where they proved to be valuable advisors and critics, offering recommendations about plans and helping to clear the way for the Center's activities in their schools. Each school system's subcontract budget paid teachers for their participation in ETC research groups and compensated the systems for burdens associated with school-based research. The ETC consortium also included a service organization funded by some 20 local school systems, which helped maintain effective communication between ETC and the schools.

"Historically teachers haven't really developed many more skills once they were on the job. So the real problem is not the technology itself, but to build the infrastructure for disseminating these skills to teachers who aren't used to asking for and/or giving help."
— *Teacher*

The superintendents appointed teachers to serve on the ETC committees that met to identify the targets of difficulty that were to become the focus of the Center's research groups. Having teachers on these committees helped ensure that the topics selected were both central to the school curriculum and recognized as difficult by many teachers and students. Then, depending on their interests and expertise, these teachers joined particular research groups, where they made crucial contributions as advisers on the design of software and other experimental teaching materials, facilitaters of school-based research, witnesses to the practical realities of life in schools and classrooms, and partners in analyzing students' responses to research activities.

ETC's experience underscores the enormous value of close collaboration with school people in conducting educational research, especially when the results are intended to improve classroom practice. At the same time, it indicates the difficulty of helping both researchers and teachers to revise their expectations, expand their skills and knowledge, and broaden their concerns to engage in true collaboration. We believe that effective collaborative research requires structural bridges between participating organizations, assistance and documentation by individuals who value the contributions of both researchers and practitioners, and time for people from different organizations to forge mutual understanding and respect.

Infusing Educational Innovations into Existing Practice

The teaching units and curriculum modules our research groups have designed can be incorporated into existing school courses and structures.

ETC research groups have designed teaching units and curriculum modules which they test and revise in increasingly realistic classroom settings. These modules include lesson plans and materials for a particular sequence of lessons. They also introduce important concepts, models, and strategies that can be integrated into other lessons to infuse an entire course with the innovative approach. The most fully developed and polished example of such an "infusible" teaching unit is the one created and studied by the ETC Programming Group.

The Programming Group began its work by analyzing the difficulties that novice programmers encounter as well as the models and strategies of the ablest students in introductory programming courses. The researchers discovered a number of misconceptions and poorly developed conceptions that interfered with students' learning. Many students lacked a mental model of the computer that would help them predict its response to particular commands. Many expected the computer to "understand" the intent of the commands they wrote, without realizing that their intent had to be expressed precisely in the formal language of programming.

On the basis of this analysis, the investigators designed a series of lessons to provide a visual model of the computer to help students envision the running of a program as an orderly step-by-step process. The lessons also taught students to ask themselves a series of questions when learning any new command: (1) What is the **purpose** of this command — in what situations should it be used? (2) What is the **syntax** of this command — in what form is the command written? (3) What is the **action** of the command

The ETC Programming Group developed materials in the form of a *metacourse* or series of lessons designed not to replace the existing course but to provide a vitamin shot to customary instruction.

— exactly what happens in the computer model when this command is executed?

The Programming Group's lessons are intended to be woven into conventional introductory courses in BASIC, but they could be modified for use with other programming languages. They are designed to be taught at intervals throughout an entire course to infuse the ideas gradually and keep earlier concepts alive through continual review. The lessons also include guidelines to help teachers use the representations and strategies as part of the classroom routine.

The modular format allows teachers to insert the lessons at various junctures depending on their schedule, students, and curriculum.

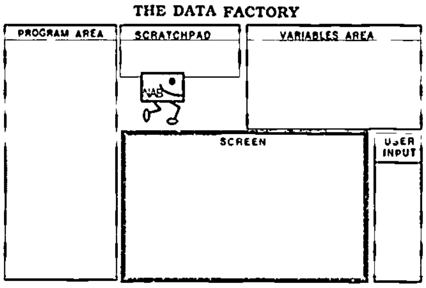
ETC calls the materials a "metacourse" because they aim to teach students general frameworks and thinking strategies that apply throughout a programming course but seldom receive adequate explicit attention. Metacourse lessons are not designed to replace an existing course or to add a new concept here and a new assignment there. Rather, they serve as a "vitamin shot" to all customary instruction. Though the lessons themselves are interspersed at intervals throughout a course, the frameworks and strategies they present become part of teachers' and students' daily repertoire for solving any programming problem.

"The Metacourse wasn't a substitute for the regular curriculum but a different, better way of presenting it. It lets you use simple ideas to develop more sophisticated procedures, it helps students recognize patterns and use them to solve more complex problems."
— *Teacher*

Field trials of the Programming Metacourse in over a dozen high school classrooms have demonstrated substantial impact on students' programming abilities, as assessed by a test that asks them to write and hand-execute simple programs. Students in classes that used the Metacourse performed significantly better than those in classes that followed the regular curriculum. These field trials also affirmed that the materials are easily incorporated into most introductory courses in BASIC. The completeness of the materials — which include lesson plans, suggested scripts for teachers, problem sets, and instructional aids such as diagrams for overhead projectors — spares teachers the burden of designing and producing such materials themselves. In addition, the format of the Metacourse allows teachers to insert the lessons at various junctures, depending on their schedule, students, and curriculum. Reports from teachers suggest that these features support effective implementation, so that the positive results obtained in teaching experiments conducted by the researchers are sustained when the course is taught under more realistic classroom situations.

Studying the Implementation Process to Understand Its Requirements

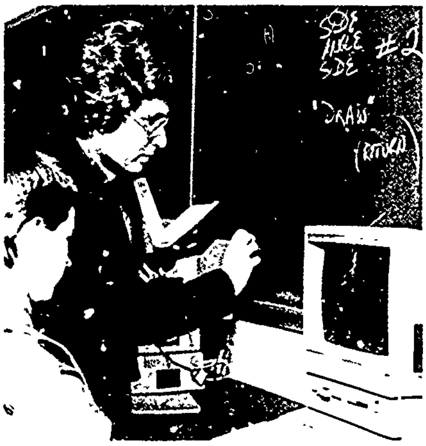
THE DATA FACTORY



During the 1986-87 school year, ETC established laboratory sites in five Massachusetts secondary schools to clarify the conditions necessary for the implementation of our approaches. ETC staff worked with the teachers in these schools to help them incorporate three innovations: the Programming Metacourse, the Heat/Temperature Unit, and the *Geometric Supposer*-based approach to geometry.

This research highlights two sets of implementation requirements. The first consists of the prerequisite conditions that must be met before sensible and effective teaching with technology is possible. Our experience in the lab sites suggests that people regularly underestimate the logistical challenges of meeting these preconditions. Acquiring, installing, and scheduling access to hardware are the first hurdles. Surmounting them may prove so taxing that few resources and little energy remain for identifying and obtaining appropriate software. In the face of such difficulties, teachers may lose interest in using computer technology.

While the new approach was a major challenge to the teachers and their students, they found it a more interesting and enjoyable way to teach and learn. Indeed, several teachers claimed that the experience had boosted their professional morale and their active involvement in mathematics.



"Computers give teachers a better opportunity to individualize, but that doesn't mean it's easy. Individualization is a difficult thing to manage. It took me two months to understand what's going on, then several more months to learn the programs and all the intimate details and intricacies of how that room worked. It took me a good year to get comfortable, but by the end of that time, my room was pretty red hot." — *Teacher*

As complex as these preparations may be, they merely set the stage for the second set of implementation tasks. helping teachers integrate a new technology into their curriculum and accustomed teaching style. This process requires a more subtle, less visible array of materials, knowledge, beliefs, and skills. Lab site innovations each involved some form of guided inquiry that attempted to build bridges between students' ideas and the teacher's intellectual agenda. In this approach, teachers:

- **present information**, including facts, explanations, and directions for activities;
- **pose problems** that provoke inquiry, challenge students' ideas, and build their reasoning skills;
- **guide students' inquiry**, providing enough guidance that students examine key concepts and practice key skills while learning how to guide themselves;
- **integrate students' ideas with the teacher's agenda**, helping students construct their understanding and build confidence in their own powers of thought, while making sure they learn the subject matter the teacher regards as important.

Lab site teachers found that implementing ETC-developed innovations required changes in their course content, materials, teaching activities, and classroom roles and routines. The amount of change depended partly on the characteristics of individual teachers, such as their knowledge and skills, and partly on the degree to which the innovation was "fleshed out" with teaching and learning materials. It also depended on the characteristics of their schools, such as curriculum requirements, and on organizational values, such as the extent to which teachers and students were expected to take responsibility for their own learning.

Lab site teachers found several kinds of resources helpful as they implemented the ETC-developed innovations. Curriculum materials — such as problem sets, teaching aids, and lesson plans — were necessary to link the software to their curriculum. Regular consultation with an experienced adviser and with other lab site teachers helped them to modify the order and content of their regular curriculum and develop new classroom management routines. Fellow innovators helped articulate problems and celebrate accomplishments. In schools where lab site innovations clashed with prevailing structures and values, teachers needed assistance from administrators to overcome or temporarily suspend organizational restrictions. For example, when the innovations addressed a broader agenda than customary tests measure, teachers needed reassurance from administrators that broader criteria would be used to assess their students' learning.

Recommendations

In the past, curriculum development projects have tended toward large-scale, whole-course efforts, or alternatively, toward the creation of well-defined, distinct modules. Each of these modes has advantages and disadvantages and both should, and no doubt will, continue as vehicles for educational reform. At ETC, we believe that two particular large-scale curriculum projects urgently need to be undertaken, and we hope to contribute to them. The first of these would be in the area of middle school science, and the second would focus on elementary school mathematics, attempting to reduce fragmentation and introduce a greater emphasis on modeling, conjecture, and inventiveness.

An Alternate Strategy for Developing Curricular Materials

ETC's work of the past several years suggests that yet another sort of effort to develop curricular materials is possible and, indeed, desirable. We have adopted the term *metacourse* for the primary vehicle to carry out this approach.

At the same time, we believe ETC's work of the past several years suggests yet another sort of effort to develop curricular materials. Different from both sharply focused modules and large-scale development projects, this proposed new mode of curricular development has certain advantages not afforded by the traditional approaches and thus complements more typical ways of going about the problem. We refer here to the approach exemplified by the Programming Metacourse described earlier; indeed, we have adopted the term *metacourse* for the primary vehicle to carry out this approach.

By *metacourse* we mean a body of material that complements and augments the existing curriculum in a subject. Metacourse materials focus on general frameworks, models, and strategies for solving problems within a discipline. They help students not only to learn specific concepts but also to understand the nature of knowledge, evidence, and argument in the subject. They are designed to infuse this kind of learning into the existing course structure, not to supplant curricular materials in present use.

Metacourses would be built on research-based educational innovations that, in their prototype form, produced promising effects on learning. They would include support materials to help teachers acquire the knowledge and skills to teach the metacourse lessons themselves, and also to infuse the key elements from these lessons into other parts of their course.

A given metacourse might consist of a set of teaching modules to be taught as individual lessons at intervals throughout a course or to be taught as one or more concentrated units during several weeks of a course. Alternatively, a metacourse might be designed to be woven into a longitudinal curriculum sequence spanning several years of, for instance, the elementary mathematics curriculum. In the case of ETC's science projects, a metacourse that stresses common infusible themes about the role of models in constructing scientific knowledge, the relationship of models to real-world phenomena, and so on was built into the Weight/Density and Heat/Temperature Units. The current Nature of Science Unit might become the first part of a metacourse on scientific inquiry that could be incorporated into any middle school science course. In elementary school mathematics, on the other hand, metacourse materials on estimation and mental calculation might become the first stepping stone toward more total curricular reform, with later metacourses following through on infusible themes concerning the structure of mathematics or the use of alternate representations. This flexibility means that metacourses could fit into larger curriculum reform efforts in varying

The heart of any research effort to use technology to improve teaching and learning must be a continued program of inquiry into the way students think about what we want them to learn.

ways. Whatever their design, metacourses would aim to influence more of teaching and curriculum than just the lessons they contain.

Several metacourses might be developed from ETC's work on particular topics, many more subjects in the fields of science, mathematics, and computing education would also be appropriate foci for metacourses. By way of example, we mention several candidate subjects that would capitalize on materials we have already developed:

- conjecture-making and proof in mathematics, in particular, in Euclidean geometry;
- measurement, intensive quantities, and the collection and representation of quantitative data from the surrounding world;
- problem-solving tactics in programming instruction;
- scientific inquiry and the use of models to develop a theory of matter.

Each of these topics addresses: (1) issues central to the discipline in question, (2) documented problems in students' understanding and active use of knowledge, and (3) an extensive body of educational research and experimentation to clarify the potential of new technologies and accompanying experimental instructional materials to alleviate these problems. Each topic presents an opportunity to investigate whether the infusion approach can have a significant impact on teaching and learning.

We believe this approach takes advantage of our findings of the last four years and provides a way to test and refine them on a wider basis. The essential premise of this approach is that the chances of achieving significant reform of science and mathematics education will be increased by infusing existing educational practice with effective teaching innovations and by letting this process of infusion lay a foundation of knowledge and skills among the participants — including researchers, developers, and school people — who might design and carry out more extensive reform. Such an incremental approach is particularly sensible when dealing with new technologies whose development and accessibility change rapidly. Moreover, such an approach brings research on learning and implementation into close association with the development of materials, to the benefit of both enterprises.

While the roots of this approach trace back to the premises with which ETC began, many of the principles reviewed here have evolved from our findings during the past four years. Accordingly, the potential contribution of the metacourse approach to wide-scale educational change needs investigation to clarify its form, assess its advantages and problems, and amplify its leverage. We strongly recommend an inquiry of this nature.

A Range of Research Questions

Three sets of fundamental questions must be studied: (1) questions about the nature of students' thinking, (2) questions about the design of curricular materials infusible into traditional science and mathematics subjects, and (3) questions about the impacts of an infusion approach on students, teachers, and schools, including the conditions necessary for effective implemention.

Continued Inquiry into Students' Thinking

The heart of any research effort to use technology to improve teaching and learning must be inquiry into the way students think about what we

"Is this a multiple choice test?" "It couldn't be — that wouldn't make sense for the stuff we've been doing."
— Two students

want them to learn. This kind of analysis must both contribute to and be informed by projects addressed more squarely to questions about teaching and implementation. For example, research on the process of changing school practices in a particular subject area can profit from a growing body of insight into the specific learning difficulties that students (and teachers) have in that subject. By the same token, research on students' thinking can benefit from an awareness of school and classroom realities.

Research on the Design of Infusible Materials

Complementing research on the nature of students' thinking in any given subject matter must be the development of materials that focus on the nature of knowledge in that subject, on what it means to solve a problem in that domain, and on the forms of evidence that are allowable and useful in that domain. For the reasons we presented earlier in this paper, we believe that computer technology, along with properly conceived and executed software, offers special opportunities for making such materials. Indeed, materials of this sort are normally developed, as they have been at ETC, in the course of carrying out research on students' thinking. Part of the task ahead is to understand better how to take research-developed innovations — innovations that are based on students' initial understandings and misunderstandings, that use computer representations to make concepts more accessible, and that guide students carefully through experiences of inquiry and problem solving — and transform them into attractive materials that teachers can use easily to complement and enhance their current teaching.

Such materials are precisely the sort that ought to be included in metacourses, where the aim would be not simply to repair isolated conceptual confusions but to influence all instruction in the subject matter. Consequently, some of the central questions about metacourse design concern the process of infusion, especially the most effective ways for teachers to remind students of key ideas and encourage them to apply those ideas in diverse circumstances within the discipline.

Research on Implementation and on the Impacts of an Infusion Approach

Part of the task ahead is to understand better how to take research developed approaches and transform them into attractive materials that teachers can use easily to complement and amplify their current teaching.

Investigating impact on student learning is a subtle matter. Given our goal of teaching for understanding, we must do more than simply gather data with traditionally accepted measures of student achievement. We acknowledge standardized test scores as the coin of the realm in many educational quarters. At the same time, we recognize their limitations for assessing the understandings and skills that our innovations promote. Assessing the impact of these innovations on students will require designing appropriate ways to discern and document these kinds of learning. To be useful to school people, such measures must work in regular school settings. Our study of impacts, then, would include the use of both traditional measures and other measures designed specifically to assess the intended results of our teaching approaches. These measures must be easy for teachers to administer and must produce information to help teachers evaluate and adjust their teaching.

For many teachers, acquiring the knowledge and skills needed to teach for understanding involves a subtle but important shift in beliefs.

Furthermore, educational researchers, including those at ETC, have become increasingly aware of other effects of innovative curricula. While the ultimate goal is impact on student learning, subtle intermediate or side effects are often worth studying. These include changes in teachers' behaviors, in patterns of classroom interaction, and in students' inclinations to pursue fur

Research must identify the materials, resources, and supports that will help teachers in regular school settings to use metacourses effectively.

"I see they know an amazing amount. Not only do they know stuff I haven't taught them, but they know stuff it never occurred to me to teach them – and they've got it in their gut."
– *Teacher*

"With computers, students are seeing teachers much more as learners, and they see that teachers are learning all kinds of things and kids are often showing teachers those things."
– *Teacher*

ther study. Investigation of these intermediate changes may help to clarify how ultimate effects on students' learning are accomplished.

Finally, to be useful and interpretable in schools, research on the effectiveness of a technology enhanced infusion approach must also attend to the constraints and opportunities that school realities pose. Research on the implementation of innovations, conducted at ETC and elsewhere, vehemently contradicts the popular notion that computer-based lessons are self-implementing. The incorporation of a new technology into a teacher's repertoire calls for attention to much more than the computer itself. In addition to access to hardware, software, and related curriculum materials, teachers need a clear understanding of the purposes of the materials, an image of how to manage teaching in the new way, and a detailed map of the subject matter they hope to teach.

For many teachers, acquiring the knowledge and skills necessary to teach for understanding involves a subtle but important shift in beliefs. Reinforced by the structure and culture of their school settings, many teachers believe their role is to transmit knowledge, as formulated and presented in textbooks. To engage students in a process that includes forming, testing, and critiquing hypotheses, teachers must accept the value of a more flexible set of teacher and student roles, and adopt a broader view of knowledge, teaching, and learning. One aim of research, therefore, must be to identify the materials, resources, and supports that will help teachers in regular school settings to make these adjustments and use metacourses effectively. Implementation must remain a central goal throughout to ensure that metacourses work easily in realistic educational settings and fit with teachers' other agendas, so that they will see widespread use.

Conclusion

While many past efforts have addressed particular conceptual problems of students, designed instruction to foster knowledge about thinking and problem solving, or incorporated new technologies into their approach, we believe that joining the three increases their power.

This essay has described an approach to curriculum development that would use metacourses as the vehicle to infuse existing instruction in science, mathematics, and computing with new approaches to teaching content, thinking, and problem solving. We enthusiastically recommend research on the infusion approach as part of a range of efforts to help students learn with deeper understanding. We believe this approach addresses many longstanding obstacles to educational change.

First, our recommendations speak directly to enhancing educational productivity by helping students understand core concepts and ways of reasoning in science and mathematics. While many past efforts have addressed particular conceptual problems of students, designed instruction to foster knowledge about thinking and problem solving, or incorporated new technologies into their approach, we believe that joining the three increases their power.

In addition, our recommendations address the difficulty of achieving wide-scale impact. We urge explicit study of the process of implementation in the conviction that attention to this process serves both research and practice. Moreover, the infusion approach recognizes that educational change must proceed progressively, building from existing practices to incorporate innovations that reflect research findings and technological advances.

ETC Projects and Products*

Science

Weight/Density
Focus: Elementary and junior high students' differentiation of weight from density, as a foundation for understanding the structure of matter.
Products. Prototype software and hands-on materials for three teaching units; technical reports.

Heat/Temperature
Focus. High school students' differentiation of heat from temperature, as a foundation for understanding energy transfer.
Products: Prototype software and teaching materials for instructional units that also use commercially available software and hardware; technical reports.

Nature of Science
Focus. Elementary and junior high students' understanding of the role of building and testing theories in science.
Products: Prototype materials for a 4-week teaching unit, technical reports.

Mathematics

Word Problems
Focus: Elementary school students' understanding of the web of ideas connecting multiplication, division, ratios, and proportions.
Products. Prototype software and teaching materials, technical reports.

Fractions
Focus. Elementary school students' understanding of fractions as continuous quantities, using the numberline as a basis for instruction.
Products: Prototype software and teaching materials, technical report.

Geometry
Focus. High school students' understanding of the role of conjecture and proof in formal mathematics, particularly in plane geometry.
Products. Prototype teaching units; problem sets; teacher training materials; technical reports. Uses commercially available software.

Algebra
Focus: High school students' understanding of graphical representations of algebraic functions.
Product: Technical reports.

Computing

Applications
Focus. Elementary and secondary school students' understanding of generic microcomputer tools such as spreadsheets and databases and effective introduction of these tools to teachers and students.
Products: Immigrant, a social studies simulation with Appleworks data files, spreadsheet, wordprocessor, teacher's guide, and manual; technical report.

Systems Thinking
Focus. High school students' understanding of a microcomputer-based dynamic modeling language and their ability to use systems dynamics in a variety of science subjects.
Products: Prototype teaching materials using commercially available software; technical report.

Programming
Focus. High school students' understanding of the structure and function of the computer and students' difficulties in learning introductory programming.
Products: Metacourse series of lessons for incorporation into introductory programming courses; teacher training materials; technical reports.

New Technologies

Computer-based Conferencing
Focus. Potential of microcomputer-based conferencing systems to reduce isolation and promote collegial exchange among high school science teachers.
Products: Microcomputer-based conferencing software, *Common Ground*, with user's manual and training guide; technical reports.

Videodisc
Focus: Potential of interactive videodisc technologies to enhance the teaching of scientific inquiry skills to junior high school students.
Products. Prototype videodisc, *Seeing the Unseen*, teaching materials, technical reports.

Speech Recognition
Focus. Potential of speech recognition technology to enhance the teaching of primary-grade reading.
Products. Technical report.

Computers and Television
Focus: Potential of computer technology when used in an integrated way with instructional television.
Products: Technical reports.

Spanning All Areas

Laboratory Sites
Focus: Research on the conditions that impede and support the implementation of ETC-developed innovations in regular classrooms and schools.
Products: Conference report; technical reports.

*A complete list of ETC products is available from the Center.

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Word Problems: James Kaput, Southeastern Massachusetts University
Geometry: Daniel Chazan, Education Development Center
Algebra: E. Paul Goldenberg, Education Development Center
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TARGETS

educational technology center

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Harvard University • Children's Television Workshop • Education Collaborative for Greater Boston • Education Development Center • Educational Testing Service • Interactive Training Systems • Public Schools of Cambridge, Newton, Ware, and Watertown, Massachusetts • Rhode Island / Brown Technology Consortium • WGBH Educational Foundation

YEAR FIVE AT ETC: *MAKING SENSE OF THE FUTURE*

This is a milestone year at ETC. As the culmination of four years of research on the uses of educational technologies to improve the teaching of science, mathematics, and computing in elementary and secondary schools, Year Five offers us a unique opportunity to reflect on our work, synthesize our findings, and communicate them to the audiences that can benefit from them. Year Five also presents the challenge of engaging with others in the formulation of an agenda for future research.

Making Sense of the Future, the booklet that accompanies this issue of *Targets,* addresses both these purposes. It presents ETC's guiding perspectives on research in science and mathematics education, distills the major findings of more than fifteen research projects, and recommends future directions for research on the use of educational technologies. We hope the ideas contained in it will contribute to the current debate and discussion about reform of the K-12 curriculum in science and mathematics. Indeed, much of what we find in our own work resonates with recommendations emerging from the National Council of Teachers of Mathematics, the Mathematical Sciences Education Board of the National Academy of Sciences, and the American Association for the Advancement of Science: develop a curriculum that begins with what students know when they enter the classroom; emphasize conceptual learning and problem solving over rote memorization of algorithms and vocabulary; help students understand what mathematics and science are and how they can be used. We believe these are important goals and, as a technology center, we have gained particular insight into when and how to use microcomputers and other available technologies to accomplish them.

This past fall, most ETC projects brought their research to a temporary stopping point. They will use the next eight months to analyze their data, consolidate their findings thus far, elaborate the themes that have emerged across projects, and mount an increasing effort to get their results into the hands of the school practitioners and curriculum developers who can give life to promising research-developed innovations. Please see the attached product list and call or write us for further information.

We hope that *Making Sense of the Future* will stimulate discussion throughout the coming months, and we welcome comments and reactions to our findings and our recommendations for future research.

A NEW CO-DIRECTOR AT ETC

On June 1, 1987, ETC welcomed the promotion of former Associate Director Martha Stone Wiske to the position of Co-Director. As a member of ETC's administration and a key architect of its directions since 1983, Wiske was a natural choice to join fellow Co-Director Judah Schwartz in guiding the Center through the final year of its current contract with the Office of Educational Research and Improvement. Wiske replaces Charles L. Thompson, who left ETC to become an associate dean at Michigan State University.

From the moment of her arrival at ETC, Wiske has been concerned primarily with shaping and putting into practice the Center's collaborative approach to research. During the early years of the Center's existence she served as the liaison between ETC and the schools, attending meetings of the collaborative research groups and helping when researchers, subject matter specialists, technology experts, and school people seemed caught in misunderstandings. She paid particular attention to supporting the participation of classroom teachers in these groups.

Last year, when ETC entered a new phase of the collaborative process by establishing laboratory sites in five Massachusetts high schools, Wiske directed the project's research. As Co-Director, she continues as lab site project leader, overseeing its investigations of how teachers incorporate technological innovations into their existing practice and how schools as organizations adapt to innovative approaches and attempt to support them. She regards the introduction of new technologies

(continued on page 2)

HOW TECHNOLOGY AFFECTS TEACHING

Teachers seldom get the chance to tell policy makers about their experiences with educational technology. During the summer of 1987, ETC in conjunction with Education Development Center conducted a study which gave them a chance to do just that. Sponsored jointly by the Office of Technology Assessment (OTA) in Washington, D.C., and the Office of Educational Research and Improvement (OERI), researchers interviewed approximately 100 teachers to clarify how they use computers, what has influenced their decisions, the effects that new technologies have in their classrooms, how they would prefer to use computers, and the resources and support they want to help them do so. By choosing teachers in ten sites across the country and including extensive users as well as those who had scarcely touched computers, researchers were able to uncover a broad range of experience and opinion.

Composite Profiles of Teachers

The project's technical report, *How Technology Affects Teaching,* was submitted to OTA and OERI in October. It contains a series of seven composite profiles of teachers, each one representing a cluster of the teachers interviewed. "Nancy Rudman," for example, typifies the teacher who is ambivalent about technology. She believes every student should learn to use computers because "they are the writing tool of the future," but she sees problems with word processing. "Kids think that because it looks neat, it's done. They haven't learned how to write and rewrite." Other teachers, represented by the profile of "Abby Miller," are eager to learn to use computers and to incorporate them into their teaching, but organizational constraints — problems with access, support services, and so on — stand in their way. At the other extreme are teachers who use computers all day every day to teach computer literacy. Most are enthusiastic about what they do but hope that before long computers will be integrated more into the regular curriclum and used more to support inquiry and problem solving.

The study also found many teachers who are already integrating computers into the teaching of mathematics and science. Like composite character "Marilyn Gordon," they find that computers allow them to do things they couldn't do before in the classroom. Simulations, for example, let students explore scientific phenomena that are otherwise impractical in school. Graphing and problem-solving programs enable students to engage in high-level inquiry and to visualize solutions to complex problems.

Recurring Themes

Asked how computers have affected their teaching, many teachers reported that the technology had helped them move away from traditional whole-class, chalk-and-talk methods. "I used to throw information at people and expect them to memorize it," as one teacher put it. With computers students work more on their own or in small groups, with the teacher circulating among them as facilitator, consultant, and coach. Though it requires them to make some difficult role adjustments and invent some new classroom management strategies, most teachers describe this change as positive and invigorating.

Researchers also asked participants what resources and supports would help them use computers more effectively. Most felt that access both in the classroom and in computer labs would be an ideal arrangement. They considered good training and follow-up assistance to be essential, and the most satisfied teachers seemed to benefit from layers of support: on-site aids to assist with logistics, a district computer coordinator to help them stay abreast of hardware and software developments, colleagues with whom to share successes and failures, a supportive building principal, and clear district-level priorities.

Policy Implications

The findings from this study suggest that computers share at least one characteristic with other significant technologies: using them effectively in schools requires an integrated system of resources. Specifically, there must be adequate hardware, appropriate software, related courseware, a knowledgeable and skilled teacher, reasonable mechanisms for assessing teaching and learning, technical assistance, and a supportive environment for teachers' professional growth and development.

Copies of this report are available from ETC. See the attached order form.

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THINKING ABOUT QUESTIONS

1. Why do radiators sometimes clang?
2. Why do jumping beans jump?
3. Should you walk or run in the rain?
4. Why does metal feel colder than wood?

A NEW CO-DIRECTOR AT ETC

(continued from page 1)

into classrooms as a chance to study alternative views of knowledge, teaching, and learning and of school culture and organization.

As Co-Director, Wiske's main priority in the coming year is the distillation and dissemination of the results of the last four years of research at ETC. She and Schwartz, assisted by ETC Associate Director Mary Maxwell Katz and the Center's senior researchers, have identified the audiences within the worlds of educational practice, policy, and research that are most likely to benefit from the Center's findings. They are currently planning a series of products and events in 1988 to carry ETC's message to those groups.

ETC PRODUCTS

To share its work with many different audiences, ETC produces technical reports and conference reports, as well as software and videotapes. These products are available at cost to all individuals or groups who request them.

TECHNICAL REPORTS present the findings of ETC's research groups. Although intended mainly for other researchers, many of them discuss the practical classroom implications of the Center's work and thus are of interest to school people as well. $3.00 each.

TR88-5 *Educational Technology Center: Fourth year report.* January 1988.

TR87-7 Programming Project: *An empirical study of a "Metacourse" to enhance the teaching of BASIC.* September 1987.

TR86-7 Programming Project: *Nontrivial pursuit: The hidden complexity of elementary Logo programming.* August 1986.

TR86-6 Programming Project: *Loci of difficulty in learning to program.* June 1986.

TR85-22 Programming Project: *Fragile knowledge and neglected strategies in novice programmers.* October 1986.

TR87-6 Systems Thinking Project. *The systems thinking and curriculum innovation project: Part I.* September 1987.

TR87-8 Word Problems Project. *A concrete-to-abstract software ramp: Environments for learning multiplication, division, and intensive quantity.* September 1987.

TR86-9 Word Problems Project: *The role of representations in reasoning with intensive quantities: Preliminary analyses.* September 1986.

TR88-4 Algebra Project: *Mathematical, technical, and pedagogical challenges in the graphical representation of functions.* January 1988.

TR87-11 Weight/Density Project: *Teaching for conceptual change using a computer-based modeling approach: The case of weight and density differentiation.* November 1987.

TR86-13 Weight/Density Project: *The role of representational features in children's learning from a computer model: A pilot study.* January 1987.

TR87-5 Heat/Temperature Project: *The differentiation of heat and temperature: An evaluation of the effect of microcomputer teaching on students' misconceptions.* December 1986.

TR88-2 Nature of Science Project: *What junior high school students do, can, and should know about the nature of scientific inquiry.* January 1988.

TR86-14 Computer based Conferencing Project. Science Teachers' Network. *Facilitating collegial exchange among science teachers An experiment in computer based conferencing.* January 1987.

TR87-12 Computer-based Conferencing Project: *Talking about teaching, by writing: The use of computer-based conferencing for collegial exchange among teachers.* December 1987.

TR87-4 Interactive Videodisc Project: *A prototype science interactive videodisc: Research on in-school use.* April 1987.

TR87-10 Special Project: *How technology affects teaching.* October 1987.

TR88-1 Laboratory Sites Project: *Teachers' thinking about students' thinking about geometry: The effects of new teaching tools.* January 1988.

TR88-3 Laboratory Sites Project: *Collaborative research goes to school: Guided inquiry with computers in classrooms.* January 1988.

TR85-20 Computers and Television Project: *The integrated design and use of computers and television in education.* July 1985.

TR88-6 Geometry Project: *Guided inquiry and technology: A year-long study of children and teachers using the* Geometric Supposer. January 1988.

CONFERENCE REPORTS summarize the themes that have emerged from ETC-sponsored conferences. $3.00 each.

CR86-4 *Teacher as learner: The impact of technology.* May 1986.

CR85-10 *The computer as a teaching tool: Promising practices.* April 1985.

CR85-28 *Computers, equity, and urban schools.* 1985.

TOPICAL PAPERS are written by ETC associates. Although not arising directly from the Center's research, they cover related topics that complement our technical reports. $3.00 each.

TP87-9 *A model program in science, mathematics, and technology.* October 1987.

TP86-3 *Information technology and mathematics. Opening new representational windows.* Prepared by James Kaput. November 1985.

TP85-25 *Intelligent computer-assisted instruction. A review and assessment of ICAI research and its potential for education.* Prepared by Christopher Dede, Philip Zodhiates, and Charles Thompson. May 1985 (draft).

SOFTWARE

SW86-16 *Common Ground.* Telecommunications system and documentation, available for IBM and DEC microcomputers. $20.00.

SW86-17 *Immigrant.* A social studies simulation for Appleworks. Includes print materials, available for Apple microcomputers. $30.00.

VIDEOTAPES produced by Education Development Center describe the uses of computers in science and mathematics education.

VT85-29 *New tools for learning. Using computers in science education.* Available in ½-inch format for $15.00 and in ¾ inch format for $25.00.

VT86-18 *Image, graph, symbol. Representation and invention in the learning of mathematics.* Available in ½-inch format for $15.00 and in ¾-inch format for $25.00

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HIGHLIGHTS

New Tools for Learning: Using Computers in Science Education **(VT85-29)** is a 27-minute videotape that presents five different uses of computers — tutorials, drill and practice, simulations and games, measurement and data analysis, and programming — and discusses the effectiveness of each one for teaching different kinds of scientific knowledge to secondary school students. ***Image, Graph, Symbol: Representation and Invention in the Learning of Mathematics*** **(VT86-18)** makes the case for multiple representations in mathematics education. Running 29 minutes, it demonstrates the use of geoboards and several types of mathematics software from the upper elementary through high school levels. Both videotapes are ideal for use with teachers, parents, and administrators. **See special offer on reverse side.**

Nontrivial Pursuit: The Hidden Complexity of Elementary Logo Programming **(TR86-7)**; ***Fragile Knowledge and Neglected Strategies in Novice Programmers*** **(TR85-22)**; ***Loci of Difficulty in Learning to Program*** **(TR86-6)**; ***An Empirical Study of a "Metacourse" to Enhance the Learning of BASIC*** **(TR87-7).** These first three of these technical reports by the ETC Programming Project discuss the findings of the group's research on the problems and successes of beginning programming students. The fourth describes the successful experimental use of a metacourse designed to help learners over their initial difficulties with BASIC.

Immigrant **(SW86-17).** This experimental curriculum unit is designed to recreate the experience of Irish immigrants in Boston from 1840 to 1860. The integrated software package includes: Appleworks™ data files with lists of passengers, jobs, and housing; spreadsheet templates that allow students to calculate food, clothing, and household expenses, and a wordprocessor. Also included is a teaching guide for a simulation in which students follow a particular immigrant family's experience.

Teachers' Thinking about Students' Thinking about Geometry **(TR87-XX).** Geometry teachers in ETC's Laboratory Sites Project use the *Geometric Supposer* with a classroom approach that encourages students to use intuition and conjecture as they work with geometric data. This technical report presents the findings of a study of how this approach affected teachers' thinking about their subject matter domain and how it might be taught.

Computers, Equity, and Urban Schools **(CR85-28).** This 50-page booklet describes a conference held at ETC in November 1984. Twenty-five participants — including urban practitioners, researchers, university faculty, and representatives from community institutions, computer corporations, and corporate and private philanthropy — met to examine the complex questions that surround the uses of educational technology in urban schools. The report also summarizes the conference's recommendations for next steps in developing sensible policies and programs.

Common Ground **(SW86-16).** This easy-to-use, microcomputer-based software, currently in use by the ETC Science Teachers' Network, is also well-suited to other electronic conferencing needs. It provides for enrolled participation, private messages, and public discussions for up to 100 members at a time. The software, available for IBM and DEC microcomputers, comes with complete documentation. The Computer-based Conferencing Project's Technical Report, ***Facilitating Collegial Exchange among Science Teachers: An Experiment in Computer-based Conferencing*** **(TR86-14),** describes just one of many possible uses of this versatile software.

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