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ABSTRACT

Developed to guide the research of the Educational Technology Center, a consortium based at Harvard Graduate School of Education, this report addresses the use of new information technologies to enrich, extend, and transform current instructional practice in science, mathematics, and computer education. A discussion of the basic elements required for a research framework individually covers the subject matter to be addressed, the pedagogical potentials of computers and related technologies, how various pedagogical styles can be employed to teach the subject matter, identification of the most crucial research topic within this framework, and a research orientation and process for addressing these topics. The following initial topics are then specified and briefly analyzed: (1) science: weight and density, heat and temperature, formulation of hypotheses, manipulating complex systems; (2) mathematics: word problems, fractions and decimals; (3) computers: functional mental models, programming and cognitive transfer, applications programs; (4) new technologies: school applications of existing videodiscs, the development of school-oriented videodisc materials, educational integration of new technologies with television, speech recognition and access to microcomputers, and non-center projects. Feedback to earlier document drafts is included and explained. (LMM)

The Use of Information Technologies for Education in Science, Mathematics, and Computers

An Agenda for Research

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INTRODUCTION

America's greatest advantage in providing for her people and protecting her interests is the nation's preeminence in science and in technology, which both applies and advances science. As the National Commission on Educational Excellence has pointed out, this preeminence has now been placed at risk, as much by decaying standards and performance in our own educational system as by intensified competition from abroad. Reinvigorating education in science and related areas is an enormous challenge requiring initiative in virtually every part of the system. The National Institute of Education—the lead research agency within the U.S. Department of Education—has responded to the challenge by creating a new Educational Technology Center.

The Center's principal task over the coming five years will be to find ways of using computer and other information technologies to teach science, mathematics, and computing more effectively. In effect, the Center will seek to bring the nation's greatest resource—science and technology—to the rescue of education, and thus to its own rescue.

Based at the Harvard Graduate School of Education, the Center is a consortium that includes Education Development Center; Educational Testing Service; the Cambridge, Newton, Ware, and Watertown, Massachusetts school districts; Children's Television Workshop; Education Collaborative for Greater Boston; Interactive Training Systems; and WGBH Educational Foundation. (See the Appendix for more information on corsortium partners and their responsibilities.)

Stated briefly, the immediate problem facing the Educational Technology Center is the deteriorating quality of elementary and secondary education in science and mathematics. Though pre-collegiate education in computer science, a technology-oriented blend of science and mathematics, is in an early stage of development rather than one of decay, its development is equally crucial. Thus, the central question guiding our research will be, "How can new information technologies be used to enrich, extend, and transform current instructional practice in science, mathematics, and computer science?"

Given this broad question and limited resources for addressing it, the Educational Technology Center needs a research framework that includes at least five elements: (1) a conception of the subject matter to be addressed, (2) a conception of the pedagogical potentials of computers and related technologies, (3) a view of how various pedagogical styles can be employed to teach the subject matter, and (4) a strategy for identifying the most crucial topics for research within this framework, and (5) a research orientation and process for addressing these topics. The sections which follow deal with the five elements in turn. The sixth section specifies the first set of topics which we have selected for study and offers a brief, preliminary analysis of these topics. The concluding section summarizes the feedback we received to earlier drafts of this document and explains our responses.

This document describes work to date on the iterative process of developing a research agenda for the Center. The research projects described here are progressing; additional topics for research will be identified as our work continues. Subsequent papers from the Center will report findings from our research and agendas for our subsequent work. Two other documents are currently available from the Educational Technology Center: one describes our training activities and the other outlines our dissemination plans.

A CONCEPTION OF THE SUBJECT MATTER DOMAIN

We believe that focusing on physical and biological sciences and on the uses of mathematics and the computer in the sciences offers a powerful, integrated way of conceiving the subject matter domain. Such an approach can motivate and provide a practical, concrete, and problem-oriented basis for understanding mathematical ideas and acquiring mathematical skills. It can provide an equally appropriate context for learning computing by doing computing.

Science, Mathematics, and Computers

In this section, we present a view of scientific knowledge which incorporates mathematics and computing. Specifically, we propose a view of science as comprising three kinds of knowledge: theoretical, procedural, and factual. Theoretical knowledge refers to models or schematic representations of phenomena. Procedural knowledge includes not only "procedural thinking skills" of the sort associated with structured computer programming (e.g., breaking a large problem up into a set of smaller, more manageable ones), but also a broad range of concepts and techniques involved in formulating questions and hypotheses, acquiring data (e.g., observation, measurement), and manipulating data (e.g., storage and retrieval, application of statistical techniques). As we conceive it, mathematics constitutes a major subset of procedural knowledge. Factual knowledge is more fragmentary and remains closer to the level of observation and measurement than does theoretical: the sun is approximately 93,000,000 miles from the earth, water freezes at zero degrees Celsius, and the human heart has four chambers. Clearly, there is a complex set of interrelationships among the three kinds of knowledge, they blend into each other in various and subtle ways, and all three are subject to evolution and revolution. But they remain useful categories for describing scientific knowledge and for approaching the improvement of education in science, mathematics, and computer science.

Theoretical Knowledge

Quite spontaneously and without much self-consciousness, children and adults try to make intuitive sense of the world around and within them. Children tell themselves stories about the world: "The moon follows me around. I saw it from my driveway, and when we got to Grandma's house, it was still up there where I could see it." Adults also tell themselves stories: "The sun and the other planets revolve around the earth." These stories about the physical and biological world may be thought of as models or schematic representations—sometimes diffuse and confused and sometimes well-defined—which people use to understand their surroundings.
Science is a way of improving our intuitive understanding of the physical world, including the parts of it that are alive. Although it is commonly obscured by the sheer complexity and technical vocabulary of modern science, there is a certain continuity from the child's self-centered model of the solar system to Ptolemy's earth-centered model to Copernicus' heliocentric model to Newton's and Einstein's progressively more precise and complete formulations. All of us reformulate our models of the world in the face of evidence or logic that undeniably contradicts them. Scientists simply exercise special care and skill in formulating models and in seeking evidence concerning their accuracy.

Too often, however, science education has presented theoretical knowledge as dry, technical, and specialized—bearing no recognizable relationship to the familiar world of everyday experience. In ways that we shall elaborate below, interactive technologies offer new ways to make vivid the connections among experience, intuition, and theory.

Procedural Knowledge

In the process of formulating and testing theories, scientists use mathematics to describe the world quantitatively, to create precise and frequently complex models of phenomena, and to check these models against data taken from observations and measurements. In this sense, mathematics may be viewed as the handmaiden of science. Obviously, mathematics is a discipline in its own right, a discipline of great logical beauty. But as an Educational Technology Center designed to help the nation respond to the challenge of international competition, we propose to emphasize the power of mathematics rather than its beauty. That is, we propose to concentrate on examining ways in which students may learn and use mathematics as they describe, model, and solve problems concerning physical and biological phenomena.

As they construct and reconstruct quantitative models, scientists rely increasingly on the computer. In this process, computers are useful tools for conjecturing or hypothesizing as well as for storing, retrieving, and manipulating data. To be sure, the computer is also a profoundly important object of study in itself. But consistent with our integrated view of science, mathematics, and computer science, we propose to emphasize the uses of the computer as a tool for understanding and affecting the world rather than Ptolemaically placing the computer at the center of the world.

In addition to its instrumental uses, the computer has also made a subtler contribution to scientific knowledge, demanding as it does a rigorously systematic approach to problem definition and resolution. To a substantial extent, structured or modular programming embodies an approach to problem solving long practiced by mathematicians and scientists. But structured programming demands an attention both to the overall architecture and to the detailed craftsmanship of thought which has undoubtedly enriched our repertoire of procedural thinking skills, thus extending the range of procedural knowledge properly considered part of scientific knowledge broadly conceived.

In addition to mathematics and procedural thinking skills, procedural knowledge in science embraces a profusion of concepts and skills involved in experimentation and investigation, such as hypothesis formulation, observation, measurement, and the like. Modern instrumentation has become extremely sophisticated technically and is tied up with the computer in diverse ways. However, the fundamental logic of investigation remains reasonably stable and accessible—an especially important point to bear in mind in an educational context.

Factual Knowledge

The "knowledge explosion" which threatens to inundate us all in a tidal wave of information has resulted in considerable measure from the application of procedural knowledge in the context of theoretical knowledge--of investigatory and problem-solving processes employed to test theory-based hypotheses. In physics, for example, the development of knowledge about subatomic particles has depended heavily on theoretical interpretation of tracks laid down by evanescent bits of matter not themselves directly observable. At times, the interplay of observation and revision of theory has been so rapid that this "knowledge" has appeared almost as perishable as the particles themselves. Virtually all scientific fields are blessed and afflicted by accelerating change in and additions to "the facts." This sustained explosion presents an enormous challenge to practicing scientists, to those who use scientific knowledge, and--to a quite dizzying degree--to educators.

Science, Mathematics, and Computers: Summary of Our Viewpoint

In summary, then, we propose to incorporate science, mathematics, and computing into an integrated view of scientific knowledge. This view emphasizes the utility of mathematics and computing in the generation and manipulation of scientific knowledge. It provides a basis for illuminating the relationship between science and everyday experience, for teaching mathematics through problem solving and the modeling of real world phenomena, and for enabling students to learn computing by using the computer as it is used by scientists and mathematicians.

A CONCEPTION OF THE PEDAGOGICAL POTENTIALS OF COMPUTERS

Modes of Computer Utilization in Education

Many, if not all, present educational uses of computers fall into one or the other of two categories: the computer as a medium or the computer as a tool. By computer as medium, we mean the use of the computer to convey to the user, or to instruct the user in, some body of knowledge. By computer as tool we mean the use of the computer to accomplish some task for the user, including the most significant task of creating new tools.

The Computer as Medium

There are four broad categories of the use of computers as instructional medium: drill and practice, tutorials, games, and simulations.
Attempts to use the computer as a drillmaster or tutor have a rather long history, and over 80 percent of existing educational software in mathematics and science falls into one of these two categories (TERC, 1983). As a drillmaster, the computer simply presents problems and checks answers. Most drill and practice programs constitute automated workbooks, in which the computer functions as a high-priced page turner. Some predominantly drill and practice programs also include limited tutoring or prompting on missed problems. As a tutor, the computer guides the student through segments of subject matter, asking questions, approving correct answers, and going back over material not mastered. Implicit in the concept of a tutorial program is the assumption that the program can interact intelligently with the user.
One can distinguish two categories of educational computer games: those that attempt to convey some portion of the content of some discipline (content games) and those that attempt to sharpen the use of a cognitive strategy that may be applicable to a variety of subject matter (process games). Increasing numbers of games that attempt to teach skills such as problem solving have recently become available (e.g., Rocky's Boots, Gertrude's Secrets, Gertrude's Puzzles).

Closely related to games are simulations, which can be used in two ways: to explore the applicability of models of the real world, and to develop insight into phenomena that cannot be directly, or easily, observed. A simulation of the behavior of a pendulum, or one of the various simulations of the Milliken oil-drop experiment, for example, can be compared to the phenomenon in nature. In contrast, programs like Birdbreed (a simulated genetics laboratory) and Three Mile Island (in which students "operate" a nuclear-powered reactor), represent simplified models of complex, real systems.

The Computer as Tool and Tool Maker

There are many computer programs available that are designed to carry out a specific task and require no programming on the part of the user. Such programs are commonly used in the business world to handle such problems as inventory control, accounts receivable, mailing lists, and telephone directories. In education, such systems are designed to help the user solve a particular type of problem. For example, a program may provide a graphic representation of data derived from a particular experimental situation--like the computer thermometer designed by Robert Tinker of Technical Education Research Centers (TERC) of Cambridge, Massachusetts, which provides a continuous reading of temperature as a function of time.

There are several more general purpose, symbol-manipulating tools that are now in widespread use. The hand calculator is everywhere, including the schools, and its utility is well accepted. Coming into equally wide use is a microcomputer extension of the hand calculator—the spread sheet program. The word processor, which has displaced the typewriter in many offices, is also beginning to find its way into the classroom. At EDC, Judah Schwartz has developed a general purpose tool called the Semantic Calculator (SemCalc). SemCalc allows the student to use the computer to carry out calculations involving both numbers and the units to which the numbers refer. Schwartz and his colleagues in the NSF-supported Dimensional Analysis Project found that SemCalc gives students and teachers a purchase on "the word problem problem" which neither group felt they had before.

It is as a creator of new tools, however, that the computer differs most dramatically from other technologies, such as the textbook, the audio recording, or television, each of which has been used both as medium and as tool in education. Each of us now has, or will soon have, the opportunity to use the computer to design a tool to fit our own perception of a task we want to perform or a problem we wish to solve.

We may have some difficulty at present in imagining how we can use such a tool or what it will mean for our lives. Yet it is likely that a generation from now every educated person will consider a procedural approach to problem solving of all sorts natural and commonplace, will be comfortable with many strategies for structuring data and representing knowledge, and will regularly create unique tools for applying these strategies.

What role the tool-making capacity of the computer should play in education today is one of a set of questions about the ends and means of education that are raised by the introduction of the computer into the classroom. We address some of these questions below.

Computer-based Education and Educational Philosophy

The computer is a Rorschach ink blot test for educational philosophy. The computer is so versatile, so rich in possibilities, that virtually any view of what education is or ought to be can be implemented on it. Thus, when many people approach the question of the computer's educational applications, they "see" in it a realization of their own beliefs about education. Yet it is important to realize that, consciously or unconsciously, we choose an educational philosophy when we choose a certain approach to the use of computers in education. The philosophy is not a "given" of the machine.

Most current thinking about education in America may be located along a continuum between two polar views, directed instruction and open education. The two views constitute ideal types rather than descriptions of actual practice in classrooms, but most educational theories and practices--whether computer based or not--may be located somewhere along a continuum between these two views. The two are therefore useful points of reference for discussing the pedagogical questions inevitably entailed in educational applications of microcomputers. Accordingly, we shall briefly characterize each approach and its consequences for computerized instruction both in general and in science and mathematics, and then turn to a third, eclectic approach which promises to surmount the limitations of the first two by incorporating their complementary strengths. The third approach addresses the need to teach all three types of scientific knowledge discussed above, and takes advantage of the full range of computer capabilities both as medium and as tool and tool maker.

Directed Instruction

For many, "education" means formal instruction, a process in which knowledge is divided into domains, within each of which a set of concepts, skills, and facts more or less agreed upon by experts in the domain is introduced to students by a teacher through presentations, assigned readings, and exercises of various sorts. Over the past twenty years or so, directed instruction advocates have technologized the ideal conception if not the practice of formal instruction in ways that bear no necessary relation to hardware. This new conception of formal instruction emphasizes analysis of what is to be taught into discrete elements, hierarchically arranged; translation of these content hierarchies into goals and specific behavioral objectives for students; and student progress through the hierarchies under strict teacher control, achieved either through methodical group instruction or through individual diagnosis and prescription.

Some varieties of directed instruction are explicitly based upon behaviorist learning theory, which sees learning as the acquisition of new behaviors through guided performance of bits of behavior followed by "reinforcement," leading cumulatively to complex behavioral repertoires. Other varieties are more loosely related to learning theory. For present purposes, however, a broad range of diagnostic-prescriptive, individually guided, and "continuous progress" programs may be viewed as variants upon the directed instruction approach. Although they differ from each other in non-trivial ways, they share an emphasis on teacher control of student progress through well-defined content domains. In this view, learning is an additive process, and while some discretion over the rate of addition may be surrendered to the student, the teacher clearly retains authority over its path.

Directed instruction lends itself readily to implementation on the computer. In fact, most computer-assisted instruction amounts to the automation or computerization of the directed instruction approach.

Traditional CAI generally uses the computer in two ways, as a tutor and as a drillmaster.

Open Education

In contrast with directed instruction's reliance on the teacher to guide the student through meticulously specified content hierarchies, open education emphasizes relatively free, intuitive explorations by the student, directed by his or her natural curiosity. To the extent that the teacher structures or directs the student's activity, it is by designing an environment rich in materials and resources and by posing problems, questions, and challenges that engage the student's interest.

In this view, grounded in Piagetian notions about cognitive development, children are more or less continuously engaged in attempts to make sense of the world around them. Exposed to diverse experiences, mentally they fashion working models of parts of the environment, and they try to understand new experiences in terms of these models. In fact, to understand something is to assimilate it into, or see it in terms of, one of these working models. When the child notices that a new experience won't quite fit any of the models already in hand—or, more accurately, in mind—the child may adjust the model. Or, as fallible scientists sometimes do, the child may doubt or deny the "data." So the child is always tinkering with the models in his or her repertoire, changing features, adding new features, or putting simple models together to make more complicated models that match up better with his or her observations.

A central claim of the Piagetian view of learning is that teaching concepts and skills didactically—that is, in isolation from experience that gives rise to an intuitive feel for the meaning of the concept or the logic of the procedures—results at best in parroting, or the acquisition of behaviors empty of understanding.

While directed instruction has lent itself readily to computerization, for some time open education seemed almost antithetical to computer implementation. The need to master one or more rather complex computer languages together with the deeper concepts of programming that underlie them appeared to stand between the pre-college student and the machine, thus ruling out autonomous exploration and problem solving with the computer by all but a few advanced high school students.

Within the past few years, however, the LOGO group at Massachusetts Institute of Technology completed development of a language and a mode of computer utilization that make computers far more accessible, even to relatively young children, than was possible previously. Particularly through its Turtle Geometry capabilities, LOGO offers a powerful but easy to learn computer language appropriate to tasks and challenges which many children appear to find engaging. Thus, LOGO makes the "tool making" capabilities of the computer available to children at an earlier age. The activity of children in a LOGO classroom or laboratory is generally consistent with open education principles.

Summary of the Polar Approaches

The differences between directed instruction and open education can be summed up in terms of their contrasting positions on three issues: (1) the role of intuition, (2) the nature of learning as an additive versus a transformational process, and (3) control. Open education views an intuitive grasp of concepts or procedures as the basis for meaningful learning; directed instruction generally ignores intuition or views it askance, as mystification. This is partly because directed instruction considers learning a process of adding up many bits of information or behavior, while open education sees learning as a matter of connecting new information or behavior with pre-existing understandings and experiences, transforming both the existing understandings and the new information in the process. Finally, because open education sees learning as an active, transformational process intimately tied to prior experience, it takes the position that the student should control the path of his or her own education as much as possible. Directed instruction takes precisely the opposite view: the teacher should control the path, pace, and details of the student's learning in order to ensure mastery of carefully engineered sequences.

APPLICATION TO COMPUTER USE IN SCIENCE AND MATHEMATICS EDUCATION

Applications to computer-based instruction in science and mathematics of both the open education and directed instruction approaches have significant weaknesses that derive from their extreme positions on the role of intuition, the nature of learning, and the issue of control.

On the one hand, the strong emphasis of the open education-LOGO approach on independent discovery or invention of concepts or principles by each child tends to exclude the teaching of important scientific ideas and facts. This has resulted in an unfortunate tendency which might be caricatured in the slogan, "Every child his own Newton." Moreover, LOGO has not generally been used to model the physical or biological world at all in any deep sense. Rather, Seymour Papert's exposition of the LOGO philosophy as well as all of the classroom implementations of LOGO which we have observed employ the language largely to create Turtle Graphic images which at most represent the world pseudo-artistically (e.g., pictures of houses, flowers, bicycles) and which more commonly amount solely to geometric designs. To be sure, some of these images reflect significant geometric understanding and emergent procedural thinking skills. These are important strengths. But too seldom has the power of LOGO been directly exploited to advance children's scientific understanding. Nor is there a clear connection between LOGO and the conventional mathematics curriculum.

In contrast to LOGO's focus on independent discovery, applications of CAI in science education (as in other disciplines) have typically discounted the utility of discovery, experience, and intuition. In the process, the importance of connecting new knowledge to what the child already knows—how the child already thinks about the phenomenon under study or similar phenomena—is also discounted. A common result appears to be the partitioning off of common sense or intuition from knowledge acquired through formal instruction.

A great challenge in science education is therefore to find better ways of integrating intuition with formal instruction so that the student is neither left to re-create the evolution of Western scientific thought de novo nor tediously plied with information which sits on the shelves of the student's mind without much affecting his or her working understanding of the world.

Another challenge is to provide all students with experience of being in control of the computer, as well as being instructed by it, or using it for routine data processing. Both individually and as a society, our lives are profoundly influenced by our relationship to the dominant technology of our time, which is clearly no longer the assembly line but the computer. A critical issue in this relationship is whether on balance people initiate and control their interactions with the machine or react to and feel controlled by it--whether the technology enhances their sense of efficacy or increases alienation and feelings of subordination. We believe that a student's experience with computers will bend the twig of this relationship.

For students whose only direct experience with computers occurs in schools, including the poor and many others, the twig may be bent in fateful ways. Exposure to computers exclusively through traditional CAI (and even "intelligent" CAI) prepares students not to take charge of the computer as scientists or engineers do, but only routinely as do clerical data processors. To be sure, the society will need clerical computer personnel, but just as surely all students deserve the opportunity to experience the computer in ways that open to a broader range of careers.

Accordingly, it is important to find more ways of enabling students to use the computer in a manner analogous to the way scientists and engineers use it: as a tool for modeling, simulation, and calculation, as well as for storing, retrieving, and organizing data. In employing the computer for the latter three functions, students need to gain experience not only with conventional data base management programs and techniques, but also with "expert systems" as they are now coming into use to aid diagnosis and treatment choice in medicine, or for structure and materials choices in certain parts of the aerospace industry,

We should stress, however, that we do not reject all uses of CAI and ICAI. Many neurosurgeons in training have relied on programmed textbooks as aids in mastering the details of neuroanatomy. Analogously, there are times when it will be important for students to master well-defined bodies of factual information. At these points, CAI—the computer-based equivalent of the programmed text—can certainly prove appropriate and helpful. As indicated above, we intend to give special attention to uses of CAI to teach facts and skills needed in the course of ongoing problem solving or investigatory tasks.

An Eclectic Approach to Computer Utilization in Education

The comprehensive approach to computer utilization in education that we propose therefore incorporates both the LOGO-open education and CAI-directed instruction approaches, but overcomes the weaknesses of both. This third approach is designed to determine which are the most appropriate modes of computer utilization for educating students in the different types of scientific knowledge. The governing hypothesis of the research program we propose is that the various modes of computer utilization (drill and practice, tutorials, games, simulations, and tools) are appropriate to different degrees and in different ways for the three types of scientific knowledge (theoretical, procedural, and factual).

For theoretical knowledge--understanding phenomena in terms of models or schematic representations--the simulation/game and tool modes appear most appropriate. Simulations model phenomena, frequently in graphic form, and permit students to gain increased understanding of a phenomenon by manipulating or playing with it in various ways. Such play may prove an effective way of mastering a model, thus laying the basis for a deeper understanding of the phenomenon than could otherwise be achieved. The tool mode--and here we include original programming by the student (tool making) as well as use of software analogous to VisiCalc or VisiPlot--permits the student to construct his or her own models of phenomena, perhaps starting with very simple models in the elementary years and progressing to quite complex models in the late high school years. An interesting midpoint between the simulation and tool modes would be partially formed or modifiable models which students could complete or reconstruct to fit observations or measurements which they make themselves.

For procedural knowledge--concepts and skills involved in hypothesis formulation, observation and measurement, quantitative representation of data, calculation, problem solving through modular programming, and the like--at least three modes of computer use seem appropriate. First, tutorials may prove useful in teaching new procedures, especially mathematical and measurement techniques, that would be useful in solving a particular problem or in creating or understanding a model. Second, a number of games designed to teach or exercise procedural thinking skills for problem solving have recently become available commercially. The questions of (1) what influence experience with such games can exert upon scientific problem solving, and (2) the ways in which they might be integrated with the elementary school science curriculum are intriguing. Third and finally, a wide variety of tool programs could prove valuable for exercising procedural skills. For example, students might use data base management programs to search specially created data bases for data or factual material required to solve problems, in the process learning about Boolean logic (e.g., "A and/or B but not C") and about classic search strategies (e.g., binary search). A number of programs designed to enable students to make and record measurements are becoming available, and these should also be examined.

It is commonplace to observe that proliferating information has rendered obsolete the notion of education as mastery over a set body of facts. But it certainly has not rendered facts obsolete. The challenge is to decide which facts are important for whom to know at what times, and to find ways of helping students acquire necessary facts rapidly and appropriately. Tutorial and drill and practice programs may prove very useful in this context. As a class or small group of students study some phenomenon, a teacher might assign one or more students to master some set of crucial facts. Simulations and games might be used in the same way. For example, a simulation might permit a student to explore the inner workings of a rocket, learning its parts, their functions, and their interrelationships. In this sense, a schematic representation of a rocket would become a kind of factual environment for students to explore. Finally, the data base management programs and data bases which students use to practice searching for information by employing Boolean logical expressions would also provide the occasion for learning facts related to a problem or phenomenon.

Figure 1, "Modes of Computer Utilization Appropriate to Three Types of Scientific Knowledge," presents a summary of the applications of different modes of computer use to the teaching and learning of different types of scientific knowledge.

A STRATEGY FOR IDENTIFYING RESEARCH TOPICS

The foregoing three sections provide us with a broad framework for addressing our central question, "How can new information technologies be used to enrich extend, and transform current instructional practice in science, mathematics, and computer science?" However, it remains for us to choose the particular topics within each subject matter domain on which research should be concentrated.

FIGURE 1. MODES OF COMPUTER UTILIZATION APPROPRIATE TO THREE TYPES OF SCIENTIFIC KNOWLEDGE

Type of Scientific Knowledge	Mode of Computer Utilization			
	Drill and Practice	Tutorials	Simulations and Games	Tools
Theoretical			Manipulating models, observing effects, comparing models with nature	Creating and modifying models
Procedural		Learning new procedures for studying a phenomenon or solving a problem	Using procedural thinking skills to solve problems, puzzles	Solving problems, making and recording measurements, performing calculations, storing and retrieving data, factual material
Factual	Mastering basic facts related to a phenomenon or problem	Learning new facts related to a phenomenon or problem	Learning facts related to a phenomenon by exploring a model as an environment	Finding and learning facts required to solve a problem, model a phenomenon

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Our strategy for choosing research topics is predicated on the notion of "targets of difficulty." That is, in science and mathematics, certain topics—some narrow, some broad—seem to plague every new complement of students who encounter them. A narrow example from elementary school mathematics is the concept of area, which students confuse with perimeter. A broader one is the basic meaning of and relationships among fractions, decimals, and per cent. Most students eventually learn cookbook methods of dealing with each mode of representing ratios and even for converting from one to another, but their understandings are fragile and break down in the face of novel questions. A broad target of difficulty from middle and high school mathematics is "the word problem problem." Year after year, improving students' ability to solve word problems appears high on the agenda of the National Council of Teachers of Mathematics.

In the physical sciences, examples abound. The frequently counterintuitive laws of Newtonian action and reaction confuse students whose spontaneous theories are more Aristotelian in nature. The notion of energy conservation through transformations is far more difficult for students to grasp intuitively and conceptually than for them to parrot. Similarly with the particle theory of matter. And what of a phenomenon which is partly wave-like and partly particulate?

Examples from computer science are not yet so perennial but equally vexing. The concept of a variable as a location in memory where a value is stored--so fundamental to programming in any language--often eludes students. At a higher level, the concept of recursion becomes a hall of mirrors for many students.

In general we think of a target of difficulty as a kind of cognitive or developmental obstacle, which if not removed from the learner's path, will impede further progress. Thus, failure to grasp the concept of place value can impede the acquisition of computational skills, failure to grasp the concept of a variable can impede the acquisition of algebraic skills, failure to grasp the concept of a procedure can impede the acquisition of programming skills, and so forth.

We offer the foregoing examples not to specify the actual topics on which we plan to concentrate research but to illustrate the nature of a "target of difficulty" as a persistently troublesome topic for all but the ablest students in mathematics, science, or computer science. Such topics represent key obstacles to students' progress in quantitative and scientific domains. These are the topics about which many people say in retrospect, "I was all right until I got to...." Our hypothesis is that they not only turn many students away from courses leading to scientific and science-related careers, but also discourage the development and use of quantitative skills in areas outside the physical and biological sciences (e.g., business, industry, agriculture, social sciences). In a sense, therefore, they represent major obstacles to the development of quantitative competence in the broader society.

Paradoxically, these obstacles also represent major opportunities. If we can find ways of helping students surmount them, schools may be able to open the path to science and mathematics-based careers to many more students, contributing not only to individual students' attainment but also to the robustness of the nation's scientific and technological capabilities. In this sense, "targets of difficulty" represent targets of opportunity, as well.

A final reason for strategic concentration of our research on targets of difficulty is that these topics frustrate teachers—even the most accomplished teachers. These are the points where teachers feel the pain and <u>want</u> the help. Our sense is that a major difficulty with previous federally sponsored efforts to improve science and mathematics education has been their remoteness from the realities of students and classrooms. The tendency in development efforts has been to take modern science or modern mathematics themselves as <u>the</u> points of departure, for a group of scientists or mathematicians to define what students ought to learn and how they ought to learn it, and to pose the new vision as a more or less radical alternative to current practice. In many cases, insufficient attention was paid to what was <u>already</u> going on in classrooms—what teachers were attempting and what students were learning and failing to learn—and to the constraints and opportunities existing realities implied.

We believe that teachers learn in the same way children and everyone else learns: incrementally, by progressive transformations in and additions to what they already know and do. Accordingly, we believe that the starting point for the work of the Center must be the current realities of classroom practice, including subject matter, materials, and instructional methods.

The actual targets of difficulty on which we shall concentrate our initial research have been selected through the agenda-building process on which we are now embarked. In each domain, we have established a working group composed of teachers and curriculum specialists, experts from the relevant disciplines, social scientists, and people with expertise in educational technologies. With teachers playing a key role, the working groups have identified candidate topics for research. Three aspects of these topics are being analyzed:

- the subject matter, itself

  Expressed as simply and clearly as possible, what concept(s) and/or operation(s) constitute the essence of the topic?

  Does this concept or operation appear fundamental to the discipline, with broad applications, or is it isolated and narrow?

- how students misunderstand the subject matter

  What misunderstandings, partial understandings, and confusions about the subject matter are most common?

- whether and how technology might be used to help students understand it more clearly

  Is the topic amenable to treatment via the computer or another information technology?

  If so, what pedagogical approach seems most appropriate, and how might it be employed?

Through this process we have identified an initial set of topics for research that are central to each subject matter domain, troublesome for many students, frustrating for many teachers, and which seem amenable to technological treatment.

As we said in the introduction, this agenda concentrates primarily on our principal research focus--the use of computers and other information technologies to improve instruction in science, mathematics, and computer science at the elementary and secondary levels. In this context, we have stressed the primacy of subject matter and pedagogy, with technology playing a subordinate, instrumental role. We have also emphasized current classroom practice as the starting point for improvement. We have quite deliberately chosen not to make the new technology itself the starting point, not to cast the central questions in terms of the potentially revolutionary consequences of the new technology. We believe that students, teachers, and schools need help, need it soon, and need it far more than they need visions of twenty-first century information utopias. In the past twenty years education has had enough of failed revolutions and manifestoes on the death of schooling. Schools need a string of solid successes.

We do believe, however, that the emerging technologies have the potential to transform the way all of us learn and that this potential deserves careful exploration in its own right. Accordingly, in a separate component of our research, we shall be examining the educational applications of increasingly powerful microcomputers, videodisc, microcomputers used in concert with broadcast television, speech synthesis and recognition, electronic networking, teleconferencing, and a variety of other innovations in information technologies. In this secondary but important component of our work, the transforming potential of new technology will be the starting point and central focus. Here we shall be asking not only how emerging technologies may be used to teach better what our schools are already teaching, but also how they are changing the answers to the perennial question, "What is worth knowing?

RESEARCH APPROACH

To find ways of using information technologies to improve education in science, mathematics, and computing, we are pursuing a collaborative research approach involving practitioners, university experts from the relevant disciplines, educational researchers, and thoughtful analysts of the role of technology in education.

Identifying topics that block students' progress and finding new paths through these obstacles clearly requires the participation of practicing teachers. To carry out the research in isolation from teachers and classrooms, or with teachers as last-minute partners in testing new treatments, is to repeat the mistakes of past reform efforts in the subject areas of concern. In our work, teachers are equal partners from the outset and remain so throughout the research process.

We hasten to add, however, that while the participation of scientists, mathematicians, and computer scientists is not sufficient to produce useful research results, it is absolutely essential. The emphasis of our conceptual framework on subject matter as a principal starting point for educational applications of technology clearly implies a central role for first rate experts from the disciplines. Analysis of targets of difficulty to clarify the concepts and operations entailed in each requires these experts' participation, as does the development of technological applications that embody a clear and powerful grasp of the subject matter.

Understanding students' misunderstandings of targets of difficulty as well as the paths through which students get beyond these obstacles demands the participation of cognitive psychologists and cognitive developmentalists. Understanding the psychosocial, cultural, and sociological dimensions of learning in the domains of interest calls for additional social scientists, and understanding how teachers and students interact with subject matter and technology in classrooms demands yet another set of educational and social science perspectives. Thus, our collaborative approach includes the participation of educational researchers from a broad range of disciplines.

Finally, thoughtful analysis of technology's role is required. Teachers, subject matter experts, and educational researchers can make substantial contributions here, but the participation of people with a long-term, special interest in technology and education remains crucial to the success of the enterprise.

While a collaborative research approach brings to the table the resources needed to make powerful, practical contributions to education, it simultaneously poses the problem of getting people from such diverse perspectives to work together. There is a long history of bad communication (accompanied, in many cases, by ill will) between university-based and school-based educators. To a large extent this stems from the different cultures of the two groups, the different demands placed upon them, and the different rewards they receive. But it also reflects an important difference in the way the two groups evaluate research. To caricature the difference somewhat, a researcher typically wants to advance theory, regardless of whether the theory helps anyone do anything better; a practitioner is interested in advances which help in his or her work, regardless of whether they correspond to theory. Each perceives the other's value system to be cockeyed, and the common result is a profoundly counterproductive division.

We do not expect to undo this history with a single center, however important its work. We can, however, increase communication and reduce the gap between researchers and practitioners in the Center's own work. To this end, we have entrusted the design and conduct of the Center's research to working groups, rather than individuals, and have constituted these groups from practitioners, disciplinary specialists, educational researchers, and experts in technology.

The Science working group, for example, includes one individual who is primarily a physicist by training, two educational researchers interested in children's evolving conceptions of scientific phenomena, and eight science teachers from school systems associated with the Center. The working groups concerned with mathematics and computing are similarly constituted. The New Technologies group currently does not include teachers, but does include their counterparts, individuals whose daily work involves the technologies in question.

Simply constructing such groups did not, however, guarantee collaboration. We have taken two kinds of measures to achieve collaboration. First, we have taken care to make participation feasible and reasonably attractive for practitioners—by holding all meetings outside of school hours, by paying an honorarium for this work, which is beyond the call of duty for elementary and secondary teachers, and through a variety of other actions. The second kind of measure is easy to describe and hard to carry out—we have exercised patience, or at least persistence. Through a series of meetings, the groups have progressed from an early formality, to a continuing substantive struggle which is marked more and more by mutual respect in spite of sometimes sharp exchanges. We expected that the process would prove difficult. It has.

The procedure each group is following includes the following specific steps:

(1) Select members. The groups were constituted as described above. Guidance from the staff of the Education Collaborative for Greater Boston and the superintendents from the four Center school systems was especially helpful in choosing the practitioner members.

(2) Hold exploratory discussions. Each group began with relatively unconstrained discussions of the members' views of interesting questions, interesting applications of technology, and tough subject matter. These discussions were designed partly to begin substantive work and partly to initiate working relationships among group members.

(3) Draw up a preliminary list of targets of difficulty. One of the principal constraints and organizers given the working groups was the focus on targets of difficulty. Somewhat surprisingly, there was general enthusiasm for and little dissent from the targets of difficulty approach. Both practitioners and university people resonated to the notion and agreed that it provided a good guide to identify research topics and a common focus for their diverse perspectives. The list of candidate targets they generated was based both on the personal experience and judgement of the participants and on a review of research in the areas.

(4) Select specific targets for initial projects. Selection of targets on which to focus our initial research projects was based on the following criteria: (1) how fundamental the topic is within its field, including the extent to which mastering it is essential to continued progress, (2) how widespread difficulty with the topic seems to be, (3) how prominent it is within the present and anticipated curriculum of the schools, (4) whether practitioners and university people agreed on the importance of the topic and wanted to participate in research on it, and (5) whether the topic seems to be amenable to technological treatment in any of the pedagogical styles here described in the foregoing conceptual framework. Obviously, applying these criteria involves considerable exercise of judgment. As a result, fierce debate has frequently marked the selection process. Yet we are now quite confident of the topics'

importance and of the working groups' ability to find new ways of attacking them using information technologies.

(5) Form subgroups to analyze the topics in greater depth and propose research plans. For each selected target or target area, a subgroup involving both university people and practitioners was formed. The first order of business for each subgroup was to analyze the target in some depth, from a disciplinary point of view, from a cognitive developmental point of view, and from the point of view of the classroom teacher.

At this point, the work of the subgroups has begun to diverge. On some topics, considerably more analytic work is required. On others, the outlines of a pilot teaching and learning experiment have emerged quite clearly. On still others, a search for relevant educational software seems the best next step. The appropriate steps and plans for attacking each target are described in reasonable detail in the Initial Research Projects section, below.

There are, however, some issues and themes in terms of which we can characterize the projected research. First, it will continue to be collaborative. All research subgroups will include both university people and practitioners, and each will have access to the full range of subject matter expertise, classroom experience, social science specialties, and expertise in technology.

Second, the research will be done mainly in two contexts. We shall be studying the interaction among student, teacher, subject matter, and technology at the level of the single student in the laboratory or other isolated setting, and we shall be studying this same set of interactions in the real world of the classroom. While most of our work will require considerable preliminary exploration in the laboratory setting, focusing largely on human factors and software design questions, we shall always move as quickly as is reasonable to research in real classrooms.

Third, while we shall employ the broad range of methods described below, at the heart of our work will be teaching experiments—or perhaps more accurately, teaching and learning experiments—that involve attempts to break through difficult topics in the domains of interest by using information technologies. That is, the typical study at the Center will involve one or more teachers using some combination of hardware and software to teach specific subject matter in a new way.

A final way of characterizing the projected research is in terms of the range of major research techniques we shall employ and the phasing of these techniques. The first three techniques listed below are particularly suited to preliminary laboratory studies. The next two use what has been learned in the laboratory to guide efficient research in the classroom context. The last two techniques, which involve input-output analysis, come into play only when less structured work is complete. Specifically, the techniques are these:

A. Unstructured observation. This involves a researcher paying close attention to what a student does and says while working with the technology. There is no attempt to code behavior into predetermined categories; the researcher does, however, take notes on the student's interaction, and it is sometimes useful to videotape the session for later structured analysis.

B. Unstructured interview. This generally accompanies unstructured observation, since it is neither easy nor realistic to ignore a student's or teacher's discussion of or inquiries about what he or she is doing.

C. Microbehavioral analysis. This involves detailed recording of students' interactions with the technology. Three such techniques are increasingly common: keystroke recording, which provides a detailed record of what the student actually did with a microcomptuer (or other technology controlled by a microcomputer); time study, which provides a record of the time the student spent on each part of an interaction; and attention study, which provides a detailed analysis of what the child was actually looking at on the video screen. The last has proven enormously effective in formative evaluation of television materials, following the pioneering efforts of Professor Barbara Flagg and her colleagues at Harvard.

D. Structured observation. This ordinarily follows analysis of preliminary hypotheses emerging from unstructured observation and interviews; the object is to search for specific behaviors so that they may be counted or correlated with other behaviors or the stimuli emerging from the technology.

E. Structured interview. Hypotheses about student-technology interaction generally presume that the student's behavior stems, in part, from his or her conscious reaction to the tool or material involved. Unstructured interviews often fail to elicit this information, since the child may be more interested in commenting on the novelty of the technology, in asking questions, or in discussing the subject matter at hand. Structured interviews make sure that certain questions get asked, but the cost—and reason they generally follow unstructured research—is the imposition of the researcher's hypotheses on the conversation.

F. Cognitive input-output analysis. This comprises the traditional set of testing and statistical techniques for evaluating the difference between what a child knows before and after interaction with educational technology.

G. Procedural input-output analysis. Much educational technology is said to have more of an effect on the way children approach problems than on their current accumulation of knowledge. This presumably translates into increased knowledge in future work, but it would be useful to have some indication of this effect soon after exposure to the technology.

Through the process outlined above, we expect to produce four distinct types of outcomes:

(1) new insights about the uses of technology in teaching science, mathematics, and computing—expressed in a series of topical papers and cross-cutting analytic papers,

(2) effective new strategies for using hardware and commercial or original prototype software to attack specific targets of difficulty—expressed in detailed descriptions of how we have used the software in laboratory and classroom settings as well as the associated research results,

(3) a set of specific "design attributes", or desirable features for software in various pedagogical styles designed to convey knowledge of different types (i.e., procedural, theoretical, factual) in the domains addressed by the Center—expressed in technical reports of interest to software developers, publishers, and practitioners choosing software, and

(4) ultimately, an integrated theory of instructional design concerned with the use of emerging technologies to teach science, mathematics, and computing—expressed in theoretical papers issued as sufficient new knowledge accumulates to warrant efforts at integration.

The next section specifies the targets of difficulty we have chosen to attack first and describes how the research techniques enumerated above will be employed in each research project.

INITIAL RESEARCH PROJECTS

The first three sections of this chapter present the initial research projects that the Educational Technology Center will perform under Task 2 of its contract (exploring the ways in which technology can help to improve the learning and teaching of science, mathematics, and computers in grades K-12). The fourth section describes the work that will be conducted for Task 3, exploring the educational potential of emerging technologies.

Each of the initial research projects examines a target of difficulty identified by one or more of the working research groups. Some of these initial projects will use technology in central ways. Others will use technology in only incidental ways during these initial stages.

The nine initial projects are as follows:

SCIENCE

a study of students' conceptions of heat and temperature and the distinction between them,

a study of the growth of the concept of matter as distinct from the concept of object,

a study of the process of hypothesis formulation,

a study of the manipulation of complex systems,

MATHEMATICS

a study of how students understand and use fractions and decimals to represent continuous quantity,

a study of students' understanding of the structure of word problems and the similarities and dissimilarities among them,

COMPUTERS

a study of naive users' functional mental models of computers,

a study of the cognitive difficulties in learning to program and the transfer of cognitive skills acquired in a programming domain to other domains, a study of the pedagogic problems in teaching the use of word processors, spreadsheets, and data bases and their potential use as tools in other parts of the elementary and secondary curriculum.

There are important reasons for the choice of each target of difficulty. There is, in addition, a coherence among them. We shall present a brief discussion of the rationale for the choice of each of the targets in the detailed descriptions of the individual projects that follow. At the end of the sections on science, mathematics, and computers, we shall focus on the thematic coherence among the set of projects in each domain.

Science

One way of thinking of the content of elementary and secondary science subject matter across the grades and across the disciplines is in terms of the study of matter and the study of energy. The first of our studies, on weight and density, deals with the intellectual precursor to the development of a theory of matter. The second of our studies, on heat and temperature, deals with an attempt to understand issues of energy content and energy transfer.

The third and fourth studies in the area of science are inquiries into two aspects of scientific process and method. The third concerns hypothesis formulation and testing. The fourth study will be an inquiry into the motivational aspects of students' manipulating realistic simulations of complex physical and biological systems, as opposed to the oversimplified and idealized systems that are ordinarily studied in the science curriculum.

Weight and Density

The Problem

In order to understand contemporary theories of the composition of matter, a student must come to understand the periodic table of the chemical elements and something of the rules that govern the allowable and non-allowable combinations of the elements into compounds.

There are several quite distinct and complicated ideas that need to be understood in order for a student to reach this level of understanding.

These include the particulateness of matter (i.e., that it is made up of discrete particles and is not continuous), as well as the fact that there is a rather limited number of elementary materials, called elements, from which all matter, from fish to integrated circuits, is composed.

In order to understand these ideas, a student must have the notion that there are properties of matter that do not depend on the shape and size of the "stuff" in question, but only on the kind of "stuff" it is. It is this necessity that brings us to the study of the problem of children's understanding of density.

The density of materials is the first physical intensive quantity the child is expected to think about in terms of an underlying model. Clearly it is related to but distinct from the weight of an object made of the material in question. Similarly, it is related to but distinct from the volume of an object made of the material in question. The density of a material is a property of the kind of materials and not of the size or shape of the object into which it is fashioned.

In addition to being important as a concept in its own right, density and its relation to weight and volume raise several important problems for science education in the elementary school years. These include:

the degree to which scientific concepts are and/or need to be embedded in theories,

the differentiation of closely related constructs,

the understanding of models, and

the understanding and reliable manipulation of intensive and extensive quantities.

The Proposed Research

The proposed study is designed to explore the reasons that students find the concept of density so difficult, and to devise instructional materials that may alleviate some of these difficulties.

A series of pre-tests designed to diagnose students' concepts of weight, density, and matter are now being designed. These pre-tests use hands-on materials in the form of blocks of materials of various kinds and volumes.

Such stimuli have the property that the two extensive quantities involved (i.e., weight and volume) are perceptually detectable and apparent. The pertinent intensive quantity (i.e., density) is not. It must be inferred from the other two. In order to move toward a set of teaching materials that will increase the sensitivity of the student to the relevant intensive quantity, we propose to make use of two model systems.

The first model system is a computer display of shapes formed by dot textures of various densities. In such a system, the two relevant extensive quantities (i.e., total number of dots and the area of the shape) are perceptually accessible, as is the relevant intensive quantity (i.e., the number density of the dots).

The second model is a set of very light styrofoam plaques with area lattices of steel ball bearings embedded in them. These plaques constitute both a physical model of the computer model system and, at the same time, a model of the original physical system.

We anticipate that a set of instructional activities that deliberately and strongly accentuates the correspondences among these systems (any question that can be posed in one has a unique image in each of the others) will serve to ease some of the difficulties now present in the teaching and learning of the concept of density.

It is somewhat difficult to anticipate exactly what grade levels will be most appropriate for the conduct of this study. If we limit the tasks to ones that can be addressed qualitatively, then it is likely that the middle elementary grades will be most appropriate. However, the problems posed with both the physical system and the two model systems can become rather subtle in quantitative ways. Our present plans call for piloting the materials in the spring of 1984 in several different grades with the aim of sharpening the tasks and their appropriateness to the grades with which we will be dealing.

Heat and Temperature

The Problem

Any interpretation of the task of educating people to scientific and technological literacy must include the need to impart some understanding of the concept of energy and its storage and transfer.

So far as we know, all energy transfer within and among chemical, electrical, mechanical, biological, geological, and other sorts of systems involves matters of heat and temperature. Our perception of time as flowing in one direction is linked in a deep way to fundamental thermodynamic notions that emerge directly from the concepts of heat and temperature.

Teachers universally report that the concepts of heat and temperature are difficult for students to learn. Even after substantial instruction at the secondary level, many college students cannot adequately distinguish between these quantities.

The physics of heat is the first contact the student has with phenomena of energy transfer, an issue of paramount importance in the study of physics, chemistry, and biology. A clear understanding of the two concepts and the difference between them is of central importance to subsequent science and learning.

The Proposed Research

The proposed study is designed to explore the reasons that students find the concepts of heat and temperature and the differences between them so difficult, and to devise instructional materials that may alleviate some of these difficulties.

A series of pre-tests designed to diagnose students' spontaneous concepts of heat, temperature, and the nature of thermal phenomena are now being designed. These pre-tests, which will also be used as post-tests, will explore whether the novice's conceptualization of thermal phenomena is similar, perhaps even identical, to the conceptualization held at earlier times in the history of science. If this is true, it is likely to help us understand better the intellectual resistance of students to the science being taught them.

Understanding the distinction between heat and temperature is but one example of the problem that students have in differentiating related but quite distinct constructs. Examples abound. Here is a short list of confused related concepts:

atomic weight/atomic number
weight/density
weight/mass
heat/temperature
electric potential/electric potential energy
force/momentum
work/power

We believe that some of the insights gained in the context of helping students to distinguish heat and temperature may shed light on the more general problem of helping students to distinguish related and distinct concepts, wherever they may occur in science (or elsewhere).

Following the examination of students' naive conceptualizations of thermal phenomena, we will carry out a specific course of instruction using a set of specially designed instructional materials, including special purpose hardware (temperature probe, heat flow probe, programmable heater) interfaced to microcomputers that will give the student direct phenomenological access to both heat and temperature in ways that clarify the difference between them.

The first set of experiments is intended to familiarize the students with the three interface devices. Subsequent experiments will deal with making measurements of temperature rise as a result of the addition of fixed amounts of heat to different volumes and different kinds of materials.

Another series of experiments will deal with cooling and heating and the insulating properties of materials. This is a particularly interesting area of inquiry because students' naive "two fluid" models of thermal phenomena (flow of heat, flow of cold) are often adequate to explain observations in this particular domain.

Experiments on phase change and the latent heats associated with change of phase is another set of experiments that can be carried out with the interface devices under development.

A final series of experiments will deal with endo- and exothermal chemical reactions and the interconversion of chemical and thermal energy.

We plan to explore students' naive conceptualizations of thermal phenomena at a variety of grade levels, ranging from middle elementary to late secondary. It is clear, however, that some of the planned instructional activities can only be carried out in a quantitative manner appropriate in a secondary school setting, while others that can be presented in a more qualitative fashion might well be appropriate in the upper elementary grades.

The Formulation of Hypotheses

The Problem

Formulating hypotheses and testing them against the phenomena one observes are, in many regards, the heart of the scientific enterprise. Students, however, are given little opportunity either to carry out or to reflect on this process of formulating hypotheses. They tend to be taught and to learn the facts and even the theories of science with little appreciation of the means by which the phenomena are observed or the theories are developed. Many processes play a role in scientific method, and some, such as classification, have been studied to some extent. Yet, little attention has been directed in a formal way to the study of how people formulate hypotheses. It is clear that if we are to improve science and mathematics education, we must, in the long run, understand this issue better.

The Proposed Research

In this study we propose to give students direct experience with scientific method by having them construct and refine theories based on their own observations of natural phenomena. We will do this in several traditional scientific domains as well as in a nontraditional one, linguistic theory.

Linguistics, in addition to being a study of a body of natural phenomena, is also a study of an aspect of the human mind. We know that people's knowledge of their language is stored in their brains and that we cannot observe it directly. We do observe speech—and on the basis of the observation of speech, we try to construct theories of language. This is precisely what is done in all science—if some object or process is not directly observable, a theory, or model, is constructed with the aim of generating the behavior observed in the system under study. The theory is deemed successful to the extent to which it can account accurately for this behavior.

The person who studies his own language in an attempt to formulate a set of hypotheses about its structure is in one respect better situated than many others who are engaged in scientific inquiry. Such a person does not need much equipment to collect the data he studies—he has in his head a knowledge of his own language. He observes his own speech and the speech of others.

As part of the study we intend to undertake, we propose to develop a curriculum unit for junior high school or high school in which students and teachers use their own language as data and work out principles that account for observed utterances. They will construct hypotheses, test them, look for counter-examples, and revise their hypotheses until they fit the data and can predict accurately.

This will be done in parallel with similar hypothesis formulating activities in other domains. Another domain under consideration involves some of the tasks used in classical Piagetian research to explore the developmental transition to formal operations, such as the study of the relevant independent and dependent variables necessary to account successfully for the motion of a pendulum.

There are several possible model systems that can be instantiated on a microcomputer that can also stimulate people to reflect on their hypothesis formulation. These include a variety of sophisticated rule-inferring games, such as the microcomputer program called King's Rule.

We are developing and assembling the materials necessary for this study and plan to pilot some of them before the end of the spring 1984 semester. We belive that the material will be appropriate to students in junior and senior high school. We are particularly interested in seeing whether an effort of this sort helps to clarify the nature of the scientific method to students and teachers. We hope to determine whether such materials and activities are realistic and, if successfully carried out, can enhance students' understanding of the processes of science that they encounter elsewhere in the science curriculum.

Manipulating Complex Systems

The Problem

There are several interesting reasons to explore the manipulation of simulations of complex systems. First, such systems frequently have sufficiently rich phenomonology that the exploration of the system leads to constant surprises and the continuing unfolding of nuance. Second, complex systems are of interest because students who are not engaged by the pristine and sparse models of traditional science curriculum may well find themselves attracted to the subject if the systems they are asked to study are "realistic" enough.

Finally, there is an important implicit lesson to be learned from the study of simulations of complex systems. No simulations capture the full complexity and nuance of the system being simulated. Every simulation is, in a real sense, someone's model of how the system in question is structured and how it functions. As computers make the use of simulations more and more commonplace, it seems to us important to understand how students understand the fact that simulations are models and not reality. Nature and simulations of nature are inevitably, ultimately discrepant. And when there is a descrepancy between nature and a model of nature, students ought to learn that nature is trying to tell them something about the models they are building and using.

The Proposed Research

The subgroup of the science working group that is planning this study has not yet reached closure on a design. What follows is an outline of the planned inquiry as it stands at the time of this writing.

The state of a complex system at some instant in time can be described by specifying the values of the levels of those elements in the system that are essential to its characterization as well as the time rates of change of the levels of those elements. If one has a complete specification of the levels of the important elements of the system, their initial values, and their rates of change, one can generate a mathematical procedure for calculating the subsequent behavior of the system in time. Most dynamical simulations have this underlying mathematical structure.

Fortunately, there exists a programming language called MICRODYNAMO, implemented on microcomputers, that makes the writing of simulations with this structure quite straightforward. We plan to use MICRODYNAMO to write two or three simulations of differing complexity.

One of these simulations will be of a system so complex as to be unexplorable by the student in the classroom, or even in the accessible environment. This simulation will also be incompatible with the time scales of a single human life, not to mention the time scales of the school year. A simulation of an ecological system containing several species with widely differing life spans and inhabiting a spatial region is an example of such a system.

A second simulation will model a system whose size and time frame are manageable enough for the system itself to operate right next to the microcomputer running the simulation of the system. A system of containers that water flows into and out of at controlled rates and that has in addition some explicit feedback mechanism is an example of such a system. Such a simulation permits exploration of the correspondence between the system itself and the simulation of the system.

Our present plans call for the design of these simulations in the spring 1984 semester, and the writing, debugging, and piloting of the simulations with junior high school students in the fall of 1984.

Cross Cutting Themes In The Science Targets Of Difficulty

Analysis of the targets of difficulty identified by the working groups (not all of which will be addressed by the initial research projects) reveals some recurrent conceptual issues. Here we discuss some of the issues for the science area. As our work progresses, we expect other cross-cutting themes to emerge. These should help us uncover the roots of our targets -- conceptual, cognitive, and pedagogic -- and point out the relevant features of strategies for overcoming such difficulties in the classroom.

Intensive and Extensive Quantity

The difficulty that students have with concepts such as density, velocity, and temperature can be seen as instances of the problems of understanding intensive quantity. It is possible to have a material with a density of 3 grams/cc yet to have neither 3 grams of the material nor a cubic centimeter of the material. Similarly, it is possible to travel at 30 miles/hour without traveling 30 miles and without traveling for an hour.

Moreover, the arithmetic of intensive magnitudes differs from the arithmetic of "ordinary" quantities. If one has two blocks of our 3 gm/cc material, each of which has a volume of 10 cc and therefore a mass of 30 grams, and one puts the two blocks together, one has a combined block with a mass of 60 grams, a volume of 20 cc, but a density of 3 grams/cc. Similarly, if you combine 30 gallons of 30° water with 20 gallons of 20° water, you add the volumes, but calculating the temperature is not so simple.

The research of Strauss, Stavy, Quintero and others shows that this difficulty with the understanding and manipulation of intensive quantity is both widespread and commonplace. It manifests itself even in the most primitive quantitative property, order.

The ordering difficulties that students encounter with intensive quantity can be understood in the following way. Consider a quantity, symbolically denoted by

$$a/b \quad (a, b > 0)$$

The quantities

$$(a+x)/b, \; a/(b-y), \; (a+x)/(b-y), \qquad x, y > 0$$

all are larger than a/b. That is a conclusion that can be arrived at without computation. Similarly the quantities

$$(a-x)/b, \; a/(b+y), \; (a-x)/(b+y) \qquad x, y > 0$$

are all seen without computation to be smaller than a/b. However, the quantities

$(a+x)/(b+y)$ and $(a-x)/(b-y) \qquad x, y > 0$

cannot be ordered with respect to a/b without computation.

Moreover, the difficulties that students have with intensive quantity that are reported in the literature on research in students' acquisition of science concepts are exactly those that mathematics teachers have been struggling with for generations under the rubric of "ratio & proportion".

We see students' difficulties with heat and temperature, molarity and concentration, density, velocity and acceleration (and, incidentally, with many fractions in mathematics) all as instances of the common underlying difficulty of manipulating intensive quantity and confusing intensive and extensive quantity.

Extending The Perceptual Apparatus

Some of the difficulty that students experience in modeling physical phenomena for themselves or in understanding scientists' models appears to result from problems of scale in space and time. Molecules and atoms are far too small to be seen. Light travels so fast that many children are puzzled by the question, "Is there any light between the lamp and the book you are reading?" At the other end of the scale are the distances between stars, or the times involved in geological folding and faulting. There is a mismatch between the distance and time constants of these phenomena and the human perceptual apparatus.

We easily discern times of the order of tenths of a second to tens of millions of seconds. We discern with our unaided eyes distances of the order of tenths of millimeters to thousands of meters. We have devised a wide range of tools to help us move out from these constrained ranges, both spatially and temporally. Microscopes allow us to peer at the small, telescopes at the distant. High-speed cinematography allows us to stretch time, time-lapse cinematography allows us to compress it.

As we move away from the comfortable ranges of our perceptual apparatus it becomes harder and harder to think of entities as having meaningful structure and processes as having meaningful temporal extent. For example, it is not surprising that a particulate theory of matter is not the sort of naive theory of matter children build. Why should they? Their senses do not tell them that most of matter is empty space. Nor is it surprising that young people think the earth always looked as the earth looks now. After all, when one goes to the beach there does not seem to be any evidence of the continent drifting.

From Percept To Concept And Back

There is another kind of extension away from the perceptually comfortable that is necessary in the study of science. Frequently, percepts are too rich to build simple models of. Even in a domain as easily available to the unaided senses as the dynamics of kicking a tin can about a schoolyard, our perceptions are too rich to allow us to build clean conceptual models of underlying mechanisms. It seems to be the case that the velocity of the can is in the direction of the applied force, but not quite. Only in the world of abstraction, in which friction is absent does it become apparent that it is the change in velocity that is in the direction of the applied force. The simple law relating force and acceleration becomes available only after we depart from the perceptually comfortable in the direction of abstraction.

The building of easy bridges between percepts and concepts is one way of characterizing the linked activities of learning and teaching science. Our science research projects are all designed to examine ways in which technologies may help students build such bridges.

Mathematics

In the deliberations of the mathematics working group, there was vigorous discussion about a variety of possible targets of difficulty. Both practitioners and academics agreed enthusiastically about the need to invest a great deal of effort at the outset in attempting to understand two particular targets of difficulty: the problems of fractions and decimals and the problem of word problems.

Word Problems

The Problem

From the classroom perspective, there is no part of the mathematics curriculum that is harder for teachers to teach and students to learn than solving mathematical "word problems." Although mastery of computation seems to correlate with word problem solving skill, there is ample evidence to support the belief that such mastery in itself is not sufficient to assure skill in dealing with word problems.

From the perspective of mathematics as a discipline, the problem of word problems is the problem of modeling. How does one decide which elements of one's surround are pertinent to the set of possible quantitative relationships that can be asserted about the situation in question?

From a cognitive developmental perspective, the problem of word problems is the problem of recognizing prototypical situations for which a given tool is appropriate. In the specific context of word problems this means recognizing, for example, that some form of addition/subtraction is likely to be useful in quantitative comparison situations or that multiplication (as a Cartesian product) is likely to be useful in the context of assessing numbers of combinations.

The Proposed Research

The central thesis of this inquiry is that an essential difficulty standing in the way of developing word problem solving skills is a deficiency in recognizing appropriate correspondences between prototypical situations and useful mathematical sets of operations.

To explore this thesis, we have designed a three-stage teaching experiment. The stages are:

Collect student-formulated word problems. The problems will be classified and the categories mapped against several different taxonomic schemes for the classification of word-problems.

We anticipate that the pattern of student-formulated word problems will not be uniform. For example, we believe that many cause/change addition-subtraction problems but relatively few comparison problems will be formulated by students, that many "rate" multiplication/division problems but relatively few combinatorial or "related rate" problems will be formulated.

Having identified those situational settings for which the appropriateness of sets of mathematical operations is not particularly evident to students, we will seek to devise teaching materials and techniques to make those sets of situations more familiar and their structure more apparent.

If this effort is successful, it should be possible to detect a change in the overall word problem solving skill of students as well as in the pattern of situations they recognize and spontaneously offer as examples of settings corresponding to useful sets of mathematical operations.

The preceeding analysis is relevant to situations whose mathematical encoding is a "one step" problem. When one encounters problems of greater complexity, there is a further complication. This complication arises from the now-explicit planning component in the problem solving process. There seem to be students who have no difficulty recognizing and using any of the semantic correspondences discussed above, who nonetheless are unable to design a solution to a problem that involves concatenating several such steps.

This spring we will carry out a pilot study to clarify which aspects of the word problem problem are dominant at which grade levels, giving us some insight about where to shift attention from (a) the choice of operations appropriate to different mathematical situations to (b) the planning component of the problem solving process.

In the course of this inquiry we will use microcomputer software that focuses students' attention on the situation being modelled and relieves them of the necessity of carrying out the arithmetic operations necessary to solve the problems they are working on.

Fractions and Decimals

The Problem

From a classroom perspective the problem of fractions and decimals is a problem of teaching a symbol system (e.g., decimal point, fraction bar), a complicated set of notational schemes (i.e., numerator and denominator, place value notation for both positive and negative powers of 10), and computational algorithms within those notation schemes.

From the perspective of mathematics as a discipline, the problem of fractions and decimals is the problem of quantifying continuous quantity, and devising a symbol system and a notation scheme that encodes that quantification.

Finally, from a cognitive developmental perspective the problem of fractions and decimals is a problem of reliably mapping the perceived properties of the continuous quantities being described onto the symbol system and the notation scheme. And vice versa.

Most researchers who study quantification at very early ages believe that children's earliest quantitative experiences are with counting. The British developmental psychologist Peter Bryant takes exception to this view. He argues that the earliest quantitative experiences that we have are with continuous rather than discrete quantity. However, even Bryant is willing to grant that these early experiences with continuous quantity primarily involve the order properties of the quantities only and not any of the metric properties.

Many children arrive at school with the rudiments of counting already in place. The extension of the counting (whole) numbers to fractions and decimals involves introducing the concept of continuous quantity as an entity with metric properties. This is a profoundly new idea that is almost never dealt with in adequate detail. In support of this hypothesis, it is sufficient to note that it is the most primitive property of this new kind of quantity, i.e. its order property that gives the most trouble. (Which is larger, 3/7 or 4/10? .01 or .009999?) The problem of attaching size to a continuous quantity, is in our view, an issue at the core of the difficulty that children have with fractions and decimals, the two most common representations of the extension of the counting numbers to measuring numbers.

One of the reasons that both fractions and decimals are hard to teach and to learn as representations of "the numbers between the numbers" is that there is no obvious infinitude of numbers between any two fractions or between any two points on a line. To be quite specific, given two points on a line, say X0 and X1, it is straightforward to imagine a point X2 halfway between them, and then a point X3 halfway between X0 and X2, and then one halfway between X0 and X3, etc. Clearly, this process can continue without end. On the other hand, is it so clear that a similar process is possible with the two numbers 3/7 and 4/9?

The problem is compounded when one begins to consider operations on these numbers between the numbers. Metaphors and mental models which were adequate for operations on whole numbers are no longer adequate. Indeed, they may be misleading. Consider, for example, the mental model of multiplication, which, in the domain of whole numbers always implies a product at least as large as either of the factors. Similarly, division, in the domain of the whole numbers implies a quotient which is smaller than the number that was being "divided up". Robert Davis of Illinois reports once being told (by an adult) that 1/2 could not be divided by 1/3 because "1/3 is bigger than 1/2".

The Proposed Research

The central thesis of our inquiry is that the notion of "between-ness", so evident in the perception of continuous quantity, is neither evident nor even salient in the symbol systems and notation schemes used to describe continuous quantity.

In order to study this notion of "between-ness", we believe that a mixture of "hands-on" and microcomputer based activities would be particularly helpful. We have designed a four-stage teaching experiment to explore the validity of the hypothesis. These stages are:

Explore "between-ness" as a notion in the context of ordering integers.

Have students make and use fractional and decimal rulers of as many sorts as are feasible with paper folding strategies. In the course of this activity, we plan to pay particular attention to the problem of equivalent fractions.

Instantiate the ruler-making activities of step 2 on microcomputers and extend them to cases not possible using paper folding techniques.

Examine the understanding of "between-ness" within the notation systems for fractions and decimals using a series of microcomputer based games that depend on the order properties of decimals and fractions.

We have reason to believe, on the basis of teachers' reports, that this effort will be appropriate not only in the grades in which fractions and decimals are first taught, but in late elementary and early secondary grades, as well.

A Cross-Cutting Theme In The Mathematical Targets Of Difficulty

Making and Extending Models

Part of the difficulty of fractions and decimals as mathematical objects derives from the fact that it is not necessarily clear to students what sorts of real settings they can be used to model. It should be noted that the problem of the arithmetic of signed numbers is a problem similar in structure and origin to the problem of the numbers between numbers.

There are occasions when it is necessary to quantify parts of one's surround that possess, in addition to magnitude, a dichotomos sense, such as left-handed or right handed, in or out, up or down, etc. It is the need to quantify such entities that led the human species to invent and use signed numbers. Unless it is clear to students what modeling problems signed numbers can be helpful with, there is little reason to expect these students to be able to compute with them in any but a rote and mechanical fashion.

This process of extension of the primitive counting numbers, is in itself, an example of an important element in the learning and teaching of mathematics. The rational numbers (fractions) lead to the real numbers (do you remember your puzzlement the first time you encountered that strange number very close in value to 3.14159265346...? How did anybody ever discover all those digits and how come they are so sure that they keep going on forever?), the real numbers lead to the complex numbers (for the first time here one encounters "numbers" that are not used for either counting or measuring! Why then call them numbers?), and to vector spaces of both finite and infinite dimension. Even the metric properties of the spaces can be foregone and even more general mathematical objects invented and studied.

Computers

In some respects, the problem of deciding on initial research projects in the area of computers was easier than the corresponding decisions in the areas of mathematics and science. Because of the combined enthusiasm for and pressure to teach about computers in the schools of the country, there is a sense of urgency and immediacy to many of the problems that were formulated in the working group on computers.

In other respects, however, identifying targets of difficulty in the domain of computers is difficult. We are handicapped by the relative paucity of experience with the subject in the classroom, especially at the elementary level, as well as by the relative rarity of teachers who have had the opportunity to be engaged in this area for long enough to be reflective about it in informed ways.

Despite these difficulties, the computer working group selected three initial studies to undertake. These are:

> a study of commonly held perceptions and misperceptions about the logical structure and function of hardware and software and the generation of a useful set of functional mental models to address these issues,
>
> a study of learning and teaching programming and the transfer of the cognitive skills acquired in that domain to other unrelated domains,
>
> a study of teaching and learning the use of applications software and its potential impact on curricular domains other than the computer itself.

Functional Mental Models

The Problem

Students encountering computers for the first time frequently have difficulty inventing for themselves workable mental models of the logical structure and function of the hardware and the software. For example, learners often do not understand where information is stored in a computer, or the fact that it may be stored in different places and in different ways, or why it is necessary to do so, and what happens to the differently stored information when the computer is turned off.

Problems of this sort deserve attention because they cause considerable confusion with students of all ages who are new to the computer. Moreover, they often lead to practical difficulties in learning to use computers for a variety of purposes.

In the course of an extended series of discussions between classroom teachers and academics, a series of such difficulties have been identified. Although obviously there are subtle and complex issues that fall under this rubric, many of them are quite straightforward and probably amenable to direct instruction. It is our hypothesis that many of the confusions of this sort that learners have reflect the lack of elementary mental models.

The Proposed Research

We plan to investigate the pedagogic utility of a set of mental models that can help teachers and students to understand:

The several kinds of memory (RAM, ROM, floppy disk, hard disk, optical storage, tape, etc) and their special roles, as well as the options for transferring information among them. In particular we will attend to the distinction between moving information from one memory device to another and copying information from one memory device to another.

The interrelations among commands, program, interpreter, other elements of system software, and the data on which they operate.

Different operating levels and modes (e.g., communicating with the operating system vs. communicating with an applications program) and, within the applications program, communicating with several different modes.

What must one do to begin an interaction with a program and why? What must one do to stop an interaction with a program and why? Clearly, the answers to these questions will depend on the particular hardware and software in question. The issue, however, is one of understanding such things as the flow of control between operating system and applications program, the possible dynamic reallocation of disk space, and the like.

The distinctions among and the likelihood of hardware errors, faulty disks, electric power irregularities, user errors (both logical and physical), as well as logical errors in the software.

With this set of initial difficulties in mind, we plan to carry out the following research plan:

During the spring 1984 semester we will confirm and extend our preliminary identification of these targets of difficulty through a series of informal case studies. These cases will be collected through classroom observations and teacher interviews in settings where people are learning to interact with the computer for the first time.

During the summer of 1984 we will develop a set of mental models that address the confusions that we observe and analyze.

In the fall of 1984 we will teach these models to students at both the elementary and secondary levels. We intend to pay particular attention to the differential effects of grade level as well as to whether the students are learning to program or learning to use applications programs, or both.

Promising models will be improved and retaught during the spring of 1985.

We believe that the absence of useful mental models is a temporary problem and will gradually fade as the society as a whole becomes more familiar with computers. Nevertheless, the problem is, at the moment, an urgent one for those who are trying to teach people to use computers in various ways. It is our conviction that this effort can make an important contribution to its resolution.

Programming and Cognitive Transfer

The Problem

The problems we plan to investigate include:

What "mindware"—attitudes, cognitive strategies, and mental models—do some students bring to their first programming experiences that helps them acquire programming skills more readily than their classmates?

What mindware (programming-specific or not) must students acquire during programming instruction in order to develop into skilled programmers?

What mindware do students acquire from programming that they might, either spontaneously or with prompting, transfer to other contexts?

The reasons for this set of questions are evident. Much of the public discussion surrounding the consideration of programming instruction in the schools center on two justifications: first, computers are increasingly a part of the world around us, and it is therefore increasingly necessary to train people to use them; and second, training people to program computers may result in their thinking more logically and rationally, not only about computer procedures, but about virtually everything else as well.

It hardly needs to be pointed out that programming is not the first school subject presumed to "help you learn to think." Similar claims have been made at various times for the study of Latin and plane geometry. It is also important to note that the continued presence of these subjects in the curriculum is always based on their intrinsic intellectual merit rather than on their presumed ability to promote clarity of thought.

There are, nevertheless, good reasons to expect that learning programming may indeed have such transfer effects. It is plausible that the precision called for in the hand-execution of a program could be of great help in the context of solving an algebraic equation or that the top-down pattern of thought needed for structured programming also suits other situations that call for planning. We hasten to add that there are many roadblocks to successful transfer--some students never acquire these skills, even in the programming context and even when skills are acquired, transfer may not occur without prompting.

After all is said and done, it is important to gain greater clarity on the question of programming and cognitive transfer not only for the specific question itself. Since we seem to be in the habit of finding subjects in the curriculum that we believe to be useful for their presumed transfer properties, it seems to us to be useful to learn more about the problem of cognitive transfer in general.

The Proposed Research

We propose to begin by studying primary students learning LOGO and secondary students learning BASIC. We will do classroom observations and interviews in an effort to determine exactly which concepts are commonly understood easily, and which regularly are difficult for students to grasp. We will compare the cognitive repertoires of the stronger and weaker students. In this way we hope to be able to identify the general mindware necessary for the meeting of the first demands of programming. These tentatively identified skills and strategies will form the basis of further inquiry. We plan this stage of observation and interview to last at least through the fall semester of the 1984-85 school year.

The analysis of the data collected during this initial phase will allow the planning of a series of tasks in both programming and non-programming settings designed to make the transfer issue as salient as possible. Doing this will require the generation of a carefully considered list of candidate skills for transfer. Skills such as "debugging" are too global and generic to be useful in this undertaking. Consider, for example, the problem of the transfer of planning skills from the programming domain to other domains. While planning is obviously a quite complex set of skills, it clearly involves the ability to modularize the elements of a problem solution. A programming language such as LOGO or PASCAL is an ideal setting to look for evidence that a student's planning activities employ these skills. Other contexts that are likely to show the presence of these skills in such bold relief include using complicated cooking recipes or assembling complicated Meccano or LEGO structures.

To the extent that resources permit, we would like to encompass the following variations in the study: degree of access to computers x elementary vs. secondary level x beginners vs. students with one year of programming experience x LOGO, BASIC, and PASCAL. It is not likely that the final study we undertake in this domain will be as varied as that. At this stage, however, we do not wish to constrain the possibilities.

We are in contact with other research groups around the country concerned with the problem of programming and cognitive transfer. We intend to plan the tasks we will use in the second stage of this investigation in close coordination with these groups so as to draw on their experience as well as to avoid duplicating their efforts needlessly.

Applications Programs

The Problem

We are interested in studying the teaching and learning of applications programs for four reasons:

> Competence in using a computer is increasingly coming to be regarded as a reasonable requirement for high school graduation. Six states now require schools to offer students exposure to computers and 37 others either recommend it officially or are considering proposals to do so.
>
> Competence with a computer implies, among other things, the ability to use applications programs. Typically introductory computer courses have four components. These are: 1) some sort of introduction to the nature of the hardware, 2) an introduction to programming, 3) the study of the uses of the most common generic kinds of applications software, and 4) an examination of some of the social and political issues surrounding

the introduction of information technology into the society in a widespread way.

Introductory courses in computers that teach the use of applications programs probably have wider appeal than do introductory courses that emphasize programming.

Learning to use applications programs can be an important way of learning some fundamental concepts in computing. In particular, what are the consequences for problem structuring and posing given the availability of these new sorts of tools? Do people structure the data they encode in different ways once they become accustomed to using data bases? Is there a difference in the way people encode data depending on whether they use relational or hierarchical data bases? Does the use of spreadsheets promote the generation of mathematical models of particular forms and inhibit the generation of others?

The Proposed Research

Although there is a growing interest in the teaching of applications programs, and in integrating these applications into the traditional curricula, we have little information about the recurrent targets of difficulty in this domain. We plan therefore, as a first step, to survey teachers of mathematics and science to determine what is being used, for what purpose, and by whom.

Having identified teachers using applications programs, we will interview a selection of them in order to understand better their perceptions of both targets of difficulty as well as targets of opportunity in the teaching of applications programs. We recognize that at this time, many teachers are themselves just learning to use applications programs and have probably not had sufficient time to reflect on both the problems and the potential of what they are engaged in.

In addition to interviewing teachers, we also plan to observe students and teachers as they go about the business of learning and teaching applications programs. We will carry out these observations both in classroom settings and in controlled laboratory settings, where the learning sessions will be videotaped for subsequent anaylsis.

We will also attempt to generate a small number of science and math curriculum applications of applications programs. While we are not yet entirely certain of the extent of the effort that is appropriate, we believe an inquiry into the presentation in writing of a reasoned scientific argument to be a valuable exercise. We believe that using a data base program to study biological classification or the phenomenological properties of the chemical elements is a potentially useful addition to a science curriculum. Simiarly, we think that using spreadsheets to model populations changing over time in response to changing external conditions can be a valuable addition to both natural and social science curricula.

Following from the study of the learning of applications programs is the exploration of the cognitive consequences of this learning for other learning efforts both in the domain of computers as well as in other domains of the curriculum. Specifically, we will look for effects on students' conceptualization of problems, their problem solving, and their willingness to engage more realistic and complex problems.

Cross-Cutting Themes in the Computer Targets Of Difficulty

Mindware: Procedural Understanding and Mental Models

As we examine these targets of difficulty, we will pay special attention to the first encounters with the computer—the first several lessons or the first few weeks of use. One striking feature of the learners' first encounters with computers and computer programs is that some catch on more readily than others. Some learners seem to grasp much more quickly than others routine matters such as the handling of disks and the different operating contexts presented by operating system, editors, and LOGO or BASIC interpreters.

Therefore, in conducting our research, we will try to identify the traits and skills that make this transition easier for some than for others. We use the term "mindware" to stand for the mental strategies and mental models that a student or teacher brings to a computing or other task. We hypothesize that those individuals who have the most difficulty with the initial phases of handling computers lack a repertoire of mindware having to do with what can loosly be called "procedural understanding". Others have already acquired relevant mindware before ever sitting down at a computer. This mindware might include having a sense of a procedure as an entity, a good intuitive grasp of simple conditional branching as it occurs in non-computer contexts, and an ability to compose simple procedures out of available primitive operations (as one has to in using a hand calculator for complex computations, for instance). As we examine targets of difficulty, we will try to identify contrasts between the facilitating mindware of students who find this learning easy with the mindware problems that characterize those learners who have the most trouble.

Both the targets of difficulty we have identified and the contemporary literature on programming suggest that, in virtually all cases, a target poses problems at least in part because the learner lacks an adequate mental model of the target. A mental model is a particular kind of mindware, a mental image of a system that a person can inspect and "run" as a way of understanding what happens in the real system. For example, understanding of variables is one of the more complex surface targets but not a terribly difficult concept if approached correctly. Consider the simple expression in BASIC: A = B. To understand what this means, the learner will benefit from a mental model including visualization of the following: (1) A and B are names that stand for locations in the machines; (2) the locations have numbers in them; (3) when a number is taken out of a location, it is copied out, not moved out leaving zero; and (4) "=" means "copy the value found in the location named on the right into the location named on the left", something quite different from its normal use in algebra and arithmetic. (Note, for example, that the statement A=A+1 is a legal BASIC statement! And A+1=A is not legal!)

A great deal of instruction in programming and the use of applications programs appears not to give students adequate mental models, and many of the students do not develop such models spontaneously. In particular, we suspect that many of the problems students encounter as they are introduced to computer hardware and software are almost entirely ascribable to lack of some rather simple mental models. We will investigate this hypothesis, and hope to find solutions fairly quickly to many of these targets. Besides our own efforts, we can benefit in this inquiry from existing research on mental models, including some in the area of programming, and from the lore of experienced teachers who have developed skills for helping students with these problems of initial encounters with computers.

Mystification, Motivation, and Lack of Context

For many people computers are intimidating and mysterious. One reason for this sense of alienation is that people lack a context for understanding what computers can and cannot do, what types of tasks are well- and ill-suited to the computer's capabilities. Without such a context students have no "story line" within which to comprehend and remember the isolated facts they are taught. Instruction that ranges ahead of any motivating context tends to leave the learner feeling disoriented and mystified.

Many features of both programming languages and applications programs (e.g., spreadsheets and data base management programs) become more meaningful only in the context of situations with which students have little experience. For instance, a student typically learns about the kinds of planning and forecasting spreadsheets are good for as he learns about spreadsheets themselves. For another example, the distinction between iteration and recursion is really not very crucial in most elementary programming situations, which only require "tail recursion". One can hardly expect students to understand recursion in LOGO well until they have some experience with problems that genuinely require full recursion.

To generalize, many aspects of programming languages and applications programs only make sense as designs that serve well particular needs. We hypothesize that students have problems with many of the persistent targets of difficulty not only because of their complexity and a lack of mental models, but because of a motivating context that is lacking or too new. We will investigate our targets of difficulty with this hypothesis in mind.

New Technologies

While the preceding research projects address Task 2, this section describes our work on Task 3, exploring the educational potential of emerging technologies. In keeping with the priorities reflected in NIE's Request for Proposals, the New Technologies group has moved somewhat more slowly than the science, math, and computer groups. Its starting point was considerably more focused in our original proposal, however, and as a result we can present reasonably specific research plans in this document. It is important to note, nevertheless, that these specifics may change as planning proceeds.

The Center's work in this area is guided by a somewhat different set of objectives than its work in math, science, and computer education. The overriding objective is to foresee, at some useful level, the issues which will require attention as new technologies become available (and are marketed) to schools. Much of our work in this area will therefore focus on technologies not yet used in schools. Accordingly, the research questions typically concern the development and distribution of educational materials using new technologies rather than the curricular implementation of such materials or their impact on teachers and students in schools.

What "new technologies" will the Center study? Our object is to study new technologies likely to be educationally useful in schools (or homes) over the next few years. These, we believe, will be a subset of the new educational and communication technologies currently being used in other contexts, such as industry-based training programs. From this perspective the possibilities are intelligent videodisc, expert systems, computers augmented with speech-recognition devices, two-way computer-driven cable, and integrated applications of more than one technology, such as videodiscs or computer games in conjunction with broadcast television.

We believe that three of these candidate technologies—intelligent videodisc, speech-recognizing microcomputers, and multi-technology combinations—are almost certain to have educational impacts in schools and homes. Our projects thus focus on these. Expert systems have enormous educational potential, but the sheer difficulty of developing them and the cost of operating them make their use in schools and homes a distant prospect. The prospects for cable-based educational systems are linked to the prospects for the cable industry, which are not rosy; moreover, much of their potential parallels that of other technological combinations, and thus there is little to be gained by studying them alone.

Our focus in this research is on two features of the new technologies: the technical and organizational requirements they impose on those who wish to use them educationally, and the human-factors issues they are likely to raise when used by school-age children. As this work proceeds, but probably not until the Center's second year at the earliest, we will move to somewhat more focused study of the impacts new technologies are likely to have on teachers, students, and learning when they are used in schools. The purpose of our initial research is to lay a solid conceptual foundation for the work to come, and this is why it is cast in hypothesis-generating, exploratory terms.

Our approach is to work with individuals or groups who use these technologies already, the Center's role being to cause some of that use to be school-oriented or to add a research dimension to existing developmental work. Four New Technologies projects are moving ahead under Center auspices, and there are four other projects at the Harvard Graduate School of Education which relate to the Center's work in this area. We will describe only the Center-based projects in any detail here.

Before turning to these New Technologies projects, it is worth pointing out that the Applications research, described in the section on computing above, in many ways bridges Task 2 and Task 3. While focused on applications software that may be useful in science and mathematics classes, this research may also examine the uses of applications software in other subject areas, as well.

School Application of Existing Videodiscs

The Problem

"Intelligent videodisc" is the abbreviated name for a technology which combines the logical and device-control powers of the microcomputer with the quality and quantity of image storage provided by a laser-read videodisc player. Generally this technology also incorporates high-fidelity sound and touch-screen or light-pen input. The result, for a user, is a video and audio display which is more faithful to real life than broadcast television, extremely easy interaction with the device (usually requiring nothing more than touching items on the screen), and apparently limitless responsiveness of the display to the user's choices. This technology also has the ability to overlay upon a video image computer-generated text or graphics, which gives it highlighting and explaining potential absent in ordinary television or non-interactive videodisc.

The quality of this device's displays and interaction come at a cost: since a given videodisc's contents are permanently prerecorded on it, what appear to be limitless responses to the user's requests are in fact limited to what the disc's creator has chosen to record on the disc in the first place. The creator of an intelligent-videodisc program must anticipate every response the eventual user might make to a given portion of the program, or failing that must constrain the possible responses at each step.

This is, in theory, a severe limitation of intelligent-videodisc technology, since it seems to exclude all but relatively fixed, narrow CAI-like applications. Experience with these devices in industry suggests otherwise: there may well be a theoretical limit on the device's usefulness, but in practice even very sophisticated programs for the device rarely approach these limits, and its educational potential thus appears to be great.

One explanation for this apparent paradox is that the video and audio fidelity of the device are such an advance that the new applications they permit far outnumber those which its pre-planning requirements exclude. That is, there may be far more pre-plannable, useful educational programs to be developed than has been widely assumed. A second explanation, not unrelated to the first, is that the success of the device in industry reflects the degree to which industrial training programs comprise pre-planned responses to predictable student requests.

The question underlying this project (and the next) is the one schools will face as the cost of intelligent-videodisc devices continues to drop. In what ways will these devices prove useful in schools? On the one hand, their advanced display facilities are likely to engage students' attention far more than computer graphics do. Moreover, they will permit technological approaches in areas, such as art history, where existing displays are too crude to be useful. On the other hand, these devices will be incapable, in theory, of supporting the kind of open-ended simulations and tools—such as LOGO, the Semantic Calculator, Snooper Troops, and Micro Dynamics—that are increasingly popular on microcomputers today, and thus may lead to an essentially regressive change in educational technology.

An essential step in considering such questions is a rough assessment of the way these devices will interact with students and teachers in the school setting. There is some evidence that students respond positively to the devices in a laboratory setting and that teachers find the development of materials for them (again, in a laboratory setting) to be fruitful rather than confining. What is needed—and the point of this project—is a sense of how such devices might be used by teachers and students in the classroom.

The Proposed Research

This research project will exploit existing materials for intelligent videodisc devices developed by Interactive Training Systems for its industrial clients. Many of its materials focus on particular tasks or skills, such as the repair of a particular instrument, and are inappropriate for school use. Others focus on more general skills, such as reducing jargon and wordiness in written communication, and might be appropriate for school use.

First, the group undertaking this study—which will comprise teachers, a researcher specializing in student-machine interaction, and one to two materials developers from ITS—will review existing materials, identify a small number that might be used in classes, and secure the agreement of ITS and its clients for the experimental use of those materials. In addition to yielding materials for classroom use, this review should provide the Center a useful overview of the form intelligent-videodisc materials have taken.

Second, the research group will identify teachers, perhaps from the group itself, who are willing to use some of the selected materials as part of an existing course. ITS (or, perhaps, another developer) will make an intelligent-videodisc device and the selected material available to each participating teacher for the period of the experiment, probably between one and four weeks.

The experiment itself will involve students using the interactive-videodisc materials with the teacher's help and supervision. Researchers will both observe the interaction and interview participants. Much of the observation will focus on the structured elements of the interaction (What did the student actually do? How often was progress through the material essentially linear, and how often backward and forward along different branches? How much time did students spend on different parts of the material?). It will also include some unstructured observation of students' reactions to the technology (How much engagement was there, and how much frustration? What did students talk about?). The interviews will focus far more on the qualitative aspects of the interaction, from both student and teacher perspectives.

The final step in the project will be to summarize what has been learned about factors affecting interaction with intelligent-videodisc technology in classroom settings. We do not see this final step as the definitive word on this technology in the classroom, but rather as a framing of the issues which subsequent developers for and implementers of the technology in schools will need to consider.

The Development of School-Oriented Videodisc Materials

The Problem

It is quite clear from laboratory-based work on intelligent videodiscs and from our current work on computers in math and science education that developing materials for this technology for use in schools requires attention to the technology itself, to the subject matter in question, to existing curricula for teaching that subject matter, and to the context in which the technology will be used. It is far less clear how developers of such materials can meet these requirements.

There is little question that meeting these requirements entails a collaborative process involving teachers, designers, technical experts, and subject-matter specialists. There are parallels between this process and Gerald Lesser's model for the development of Sesame Street and other CTW programs. The technology in question has been inaccessible to school-based educators, however, and will remain so in the near future. It seems important, if intelligent-videodisc is to realize its educational potential, to understand better the development process it will require.

The question underlying this project is: How does the process through which school-oriented videodisc materials are developed unfold, and how does it seem to influence the materials which emerge? This project complements the first project described above. Here as well, we seek not a definitive answer to the question, but a framing of the issues based on careful study of one or two instances.

The Proposed Research

We plan to study one or two instances of videodisc materials development. There are several possible subjects for this research, among which we have not yet made our selection. One possibility is the development of a high-school physics unit currently being carried out by a group of teachers from Lexington and Lynnfield, Massachusetts, with the support of the Digital Equipment Corporation. A second possibility involves an attempt by David Nelson at EDC and Uri Haber-Schaim at Boston University to re-cast a wide range of film materials from the PSSC Physics curriculum in videodisc format, and to construct software permitting interactive access to those materials. A third possibility, considerably more tentative, involves developing a junior-high science unit through a collaboration among individuals involved in the Center's science working group, corresponding individuals from the Center's Senior Research Group, and technical experts from Digital Equipment Corporation.

Whatever research subject(s) we choose, the procedure will parallel that we describe for the television project below: the Center will contribute to the development project sufficient resources to produce an analytic chronicle of its progress. The focus will be both on the ways individuals with different expertises work together and on the use of research findings--in particular, about student/machine interaction--to guide development.

The products of these studies will be a cumulative series of analytic descriptions of the process, and a thematic summary of what emerges from the series. These should provide a very good sense of the principles which ought to underlie the development of school-oriented educational materials for intelligent videodisc devices.

Educational Integration of New Technologies with Television

The Problem

Broadcast television is without question the dominant educational technology. It has been used effectively from preschool to postgraduate levels, in a variety of subject areas. The great limitation of broadcast television is its noninteractivity: viewers can neither influence what they see (except over long periods of time) nor retain automatically any portion of what they have seen. There has been some success in bypassing these limitations, ranging from phone-in influence on live programming to teacher's guides, transcripts, magazines, and other materials supplementing the broadcast shows.

Current computer and communication technologies make possible the creation of shows which accept and respond to viewer comments, the presentation of non-broadcast materials on video screens which extend broadcast materials, and the transmission of other kinds of material in conjunction with a broadcast signal. The technology exists for a computer to overlay on a broadcast image appropriate text of highlights, or for a microcomputer to recieve software for a game at the same time a child is watching the broadcast show which serves as the basis for the game. It is also possible to produce a videodisc which encompasses video and text segments supplementing a broadcast show, and to write software which integrates the different media as the user wishes. Standardization remains elusive, but otherwise the technical issues surrounding these possibilities have been resolved. The question is how to produce, connect, and distribute materials which are designed to extend and amplify the educational potential of broadcast television.

How does the process through which integrated materials are developed unfold, and how does it seem to influence the materials which emerge? More specifically, how does an organization with a long history of educational service through television extend one of its successful broadcast shows using other technologies? The obstacles to this extension are potentially substantial: resources might be diverted from broadcast production, skill requirements for staff are different, licensing and subcontract issues are complex, competition is far more widespread, the choice of technologies to use for extension is enormous, and so on. Moreover, the development process ought to draw on research describing the interaction between technology and its intended audience, yet such information is difficult to discover and to use.

These obstacles may be great enough to preclude successful development. Yet, the potential for educational service is also great, and thus the obstacles are worth attacking. We plan to examine these issues as they arise in real situations, and thereby begin to understand the factors affecting the integration of various technologies into specific educational products.

The Proposed Research

We will study major attempts to extend particular successful educational television shows into related, technology-based materials. The initial subject for the research will be the effort underway at WGBH Educational Foundation to develop and distribute materials for intelligent-videodiscs and microcomputers which will extend the impact of its enormously successful science show NOVA. A subsequent project will proceed similarly using CTW's development of materials based on 3-2-1-Contact as the subject.

The Center will not contribute to the development work of the Special Telecommunications Services group at WGBH or of the CTW staff. Rather, it will provide research support to permit the groups' work to yield not only the intended products but also an analysis, primarily organizational, of the way the group approached and carried out its work. The Center will compensate the WGBH and CTW staff for the time they devote to Center-oriented analysis and will support non-participant observers and chroniclers of the process.

The model for this research project is the analysis of Sesame Street's development undertaken by Gerald Lesser. Like most exploratory research on organizational process, its precise course is difficult to predict, but it is clear that the project will emphasize analysis of the development group's structure, interviews with individuals involved with the project, and attention to key events in the development process. The product of the research will be a series of reports which describe and analyze the development and distribution process. As these accumulate the research team will identify recurrent themes and events in the study, and after a period of twelve to twenty-four months we expect these to be stable enough for analysis and reports to become more definitive and less exploratory.

Speech Recognition and Access to Microcomputers

The Problem

Children ordinarily learn to speak quite well before they learn to write; the same is true for listening and reading. Even adults often find oral communication simpler than written communication. Until recently communication with computers required written communication, using keyboards and text screens. For this reason there was little attention to the relative merits of written and other forms of communication with computers, for children or adults.

There has been great progress with speech-recognition and speech-synthesizing technology for computers. The cost of such devices has now dropped to the point where it is beginning to be reasonable to think about equipping home or school microcomputers with this technology and creating software which takes advantage of it. But there is no clear sense of what audiences and what subject matter would benefit from this.

The Proposed Research

Does speech-recognition technology enable children too young to type to use educational software on a microcomputer? We focus on this question, rather than more general questions about differences in access among adults, because the assumption that keyboard skills were essential has had a profound influence on the application of microcomputers. As is true for many other Center projects, we approach the general question through a more specific one, the answer to which should guide more general work: How do young children react to early-reading software which uses speech-recognition hardware and does not require typing? Our interest in this specific question stems not from its subject matter—reading—but from the fact that it involves the interaction between microcomputers and a new audience for them, children too young to type.

Education Development Center, in cooperation with Dragon Systems Inc., has developed software which "learns" how a student says roughly sixteen to thirty-two words and then provides stories and games in which children read the words. Our question is not whether the software provides good reading instruction, but whether the speech-recognition device in fact makes it possible for a young child to make effective educational use of a microcomputer.

The research group for this project will include experts in student/computer interaction, child observation, and reading. It will draw primarily on relatively structured observation of children's interaction with the software and hardware, supplementing this with some interviewing of the children involved. We expect most of this work to be laboratory-based at the outset, although some school-based work is possible later on.

Non-Center Projects

Four additional projects being conducted elsewhere in the Harvard Graduate School of Education relate clearly to the Center's new technologies work, even though they fall outside the Center's subject-matter focus. Two involve language arts, the third involves social interaction, and the fourth involves educational philosophy.

The first related project, directed by Colette Daiute, concerns the use of word-processing software to improve students' writing, both by minimizing the mechanical awkwardness of working with paper and pencil and by enabling students to collaborate on pieces of text. Daiute's research focuses on seventh graders, variously giving them access to traditional writing tools, to common word-processing software such as her own versions or Bank Street Writer, or to minicomputer-based editors which permit several cildren to work simultaneously on a given document.

The second related project, directed by Jeanne Chall, concerns the appropriate balance among different media, including traditional readers and computer software, in the teaching of reading. The project currently involves an extensive review of different approaches and their suitability for different audiences and levels.

The third related project, directed by Courtney Cazden, concerns the social interaction among students who are working with computers in school. The study is broad, since there has been relatively little structured attention to the issues involved.

The fourth related project, directed by Israel Scheffler as part of the general work of the Philosophy of Education Research Center, is an inquiry into the philosophical underpinnings and implications of the current enthusiasm about educational technology, both as it has evolved and as people have thought it would evolve.

We maintain close communication with the directors of these complementary projects. Our proximity permits us to exploit the mutual assistance we can offer and to avoid duplication of effort.

CONCLUSION

In summary, the research mission of the Educational Technology Center is to find ways of using new information technologies to improve elementary and secondary education nationwide, principally in the areas of science, mathematics, and computing. In carrying out this mission, we are taking a collaborative research approach involving experts from the subject matter disciplines, teachers, educational researchers with a variety of social science backgrounds, and specialists in educational applications of technology. Collaboration among these diverse partners is designed to ensure that our research results will be relevant to real educational contexts, as well as theoretically powerful and methodologically sound.

Working together, the research partners have identified a series of topics that present obstacles to many students' progress. From the identified "targets of difficulty", the research working groups have selected a subset that seems fundamental to the disciplines, especially difficult to teach and learn, and amenable to technological treatment. In terms of the conception of the subject matter domain presented earlier, these fall largely into the categories of theoretical and procedural knowledge rather than the simply factual.

Each of the targets of difficulty is being analyzed further from the several viewpoints represented in the research working groups. Subgroups are also formulating strategies for attacking the targets, generally employing the stimulation, tool, and tool-making approaches described in our earlier discussion of pedagogy and technology. As these strategies crystallize, the groups are designing teaching and learning experiments which use commercial or original prototype software to address the topics. The experiments will be carried out both in laboratory settings with teachers and students, and in classrooms. At present. most subgroups are exploring their topics more deeply and putting together pilot research projects.

In general, then, our approach emphasizes close analysis (1) of subject matter in the domain of science, mathematics, and computing, (2) of the difficulties students encounter in attempting to master the subject matter, and (3) of the pedagogical issues entailed in using technology to overcome these difficulties. We believe that only after thoughtful attention to what is to be taught can these questions of the role of technology in education be addressed effectively.

For a significant fraction of our research, however, we take the new technologies themselves as the starting points. Recognizing that emerging technologies represent dramatically new potentials for education, we are exploring some of these potentials as subjects for research in their own right, without limitation as to subject matter. Accordingly, a research working group on new technologies has selected a set of particularly promising developments and has begun inquiring into their implications for education.

From all of our research, we expect to produce four main types of outcomes: (1) new insights about the uses of techology in teaching science, mathematics, and computing, (2) effective new strategies for using technology to attack specific targets of difficulty, (3) design attributes for effective software in a range of pedagogical styles, and (4), ultimately, an integrated theory of instructional design for information technologies in education. We recognize that the last of these may be excessively ambitious, but we set it as a goal for ourselves to emphasize the need for almost continuous efforts at integration.

Responses from the Field

We distributed an earlier draft of this agenda to some 200 individuals and organizations, including chief state school officers, members of Congress, businessmen and industrialists, and organizations representing governors, state legislators, state and local school boards, local superintendents, principals, teachers, parents, scientists, mathematicians, specialists in science and mathematics education and in educational technology, educational researchers, and other interested citizens. These contacts resulted in over 50 responses, many of which were extended and substantive.

The response from these external audiences indicated a gratifying interest in the ETC work and, in most cases, an endorsement of both our general approach and our specific research projects. The feedback also helped to clarify the opportunities, constraints, and dilemmas which shape our research and define its context. In many cases commentators suggested clarifications and revisions which we have incorporated into this final draft. Three general topics recurred in the responses to our preliminary research agenda: the target of difficulty strategy, equity, and the content of particular research projects.

Target of Difficulty Strategy

We expected that putting subject matter and pedagogy first and technology second would prove a controversial approach. In fact, the feedback on this strategy was overwhelmingly favorable. "Focusing your research program on the instructional problems of existing disciplines rather than starting with microcomputer technology and searching for outlets for it is, of course, the right way to approach things," was a typical comment. While endorsing the overall approach, several commentators identified issues that must be kept in mind to balance this approach.

Some commentators have worried that our focus on a subject matter would overshadow pedagogical aspects of targets of difficulty. We recognize, however, that characteristics of students, teachers, and classrooms influence the learning process. Accordingly, while our projects are defined in terms of subject matter, the research will examine the multiple forces affecting interactions among learners, teachers, educational technology and subject matter.

A few commentators argued for an approach that takes the revolutionary new potentials of information technologies as the main point of departure. We believe, however, that realizing new technologies' potentials, as distinguished from identifying them and exploring their limits, is best achieved by bringing them to bear on important subject matter, in practical ways, now.

Further, too much discussion of the new technologies focuses on them as means while losing sight of ends. As Albert Einstein lamented, "Proliferation of means and confusion of ends seems to characterize our age." We believe it is essential to "realize the potential" _for_ something important, the immediate something being the achievement of broader, deeper scientific and quantitative literacy in the society. Having said this we hasten to add that a complex, dynamic society such as ours faces numerous challenges, with new ones developing constantly. To lay a firmer basis for addressing a broad range of challenges, we must identify and explore the educational potentials of emerging technologies as a task in its own right. Accordingly, we have initiated examination of several new technologies or new combinations of technologies.

This task is undertaken primarily by the New Technologies group. The work of the New Technologies Group will expand the boundaries of our work in several ways. Their investigations will not be restricted to mathematics, science, and computer science, but will range freely across a variety of domains. Nor will they focus exclusively on school-based education. The experimentation with computer-augmented broadcast television goes to the question of education in the home and other settings. Finally, the emerging technologies research will take us well beyond the microcomputer as a medium. Videodisc, a technology whose time in the schools will doubtless arrive in the next few years, will receive special attention, as will other technologies currently too expensive or fragile for school use.

In addition, some subcommittees of the working groups in science, mathematics, and computers will explore the new opportunities afforded by technology. For example, one project of the Science Working Group will examine ways in which technology may help teach students about multivariate systems, a topic so complex that it is usually omitted from the science curriculum. One subcommittee of the Computer Working Group, after studying current uses of applications software, will explore the untapped potential of spreadsheets, data bases, and word processing programs for education.

Though its boundaries are thus expanded, the agenda presented here does remain limited in significant ways. For the portion of its work supported by NIE, the Center's research will be restricted to elementary and secondary education. We will undoubtedly undertake research at the postsecondary level, but funding for such work will come from other sources.

Another kind of limitation on our work is implied by our focus on targets of difficulty in the subject matter domains. Consistent with our interpretation of NIE's interests and our own sense of priorities, we have chosen to defer research on the many difficult questions surrounding training in the use of and implementation of new technologies, including questions of organization, staffing, and management of the change process. These are clearly questions deserving careful examination, but we have put them aside for now, largely on the twin assumptions that others are pursuing such questions and that it is crucial to make certain that we have something worth implementing before expending too many resources on finding out how to implement it.

Equity Issues

Many respondents hoped that the Center would help reduce inequities in the use and effects of educational technology. This concern arises in several forms. The Center's work will respond in different ways to the different formulations. In this section we will outline first the forms of equity issues and then our responses to them.

Issues

School Resources. A major form of inequity is unequal distribution of resources, both across schools and within them. At this level inequity results when some students have access to microcomputers and others do not. Generally the maldistribution results in a disproportional flow of technological resources to schools and students already well endowed with educational resources. If students who possess fewer existing educational resources also receive fewer technological resources, then technology may increase rather than decrease the gap between haves and have-nots.

Home Resources. In many relatively affluent school systems the impetus for using educational technology comes from parents, many of whom have already purchased home computers and want to work with the school to help their children use them. In many less affluent systems, on the other hand, the major impetus for the use of technology comes from teachers, students, school administrators, and sometimes potential employers; few homes in such communities boast home computers, and thus the school experience with computers is students' only experience with them. These differences often tend to correlate with school-resource differences, and thus also tend to exacerbate existing inequities among students and schools.

Support. There are instances where hardware and software shortages seem not to be a problem, relatively speaking, but where not all students receive the intended resources. The problem, in general, is that schools are unable to provide the kind of support educational technology requires, e.g., staff development, technical assistance, space, supplies, schedule modifications, and so on. Providing computers to a school but leaving it unable to use them is of little use, and if the schools which are unable to use them are also disadvantaged in other ways — as often is the case — then inequities will grow worse.

Sex Differences. Accumulating evidence indicates that fewer girls than boys have access to computers and that, even when their access is comparable, fewer girls choose to use the available computers. The reasons for these findings are myriad. The results threaten to exacerbate existing differences between boys and girls in mathematics and science exposure and achievement. These sex differences appear to represent another instance of technology-driven inequity.

Expectations and Uses. A more subtle yet potent inequity in the effect of educational technology, which both stems from and contributes to some of the other inequities listed above, has to do with the uses of computers. One major challenge in education is to provide all students with experience of being in control of the computer, as well as being instructed by it, or using it for routine data processing. Both individually and as a society, our lives are profoundly influenced by our relationship to the dominant technology of our time, which is clearly no longer the assembly line but the computer. A critical issue in this relationship is whether on balance people initiate and control their interactions with the machine or react to and feel controlled by it -- whether the technology enhances their sense of efficacy or increases alienation and feelings of subordination. We believe that a student's experience with computers will bend the twig of this relationship.

For students whose only direct experience with computers occurs in schools, including the poor and many others, the twig may be bent in fateful ways. Exposure to computers exclusively through traditional CAI (and even "intelligent" CAI) prepares students not to take charge of the computer as scientists or engineers do, but only routinely as do clerical data processors. To be sure, the society will need clerical computer personnel, but just as surely all students deserve the opportunity to experience the computer in ways that open to a broader range of careers.

When some students are expected to use open-ended software to explore conjectures in a given domain while others are expected to learn a list of facts from a piece of drill-and-practice CAI software, it is logical to expect different outcomes from the two groups. This is acceptable only if the different expectations correspond in a productive, rational, and socially defensible way to the needs and capabilities of the students. It is insidious when it merely reflects and reinforces biases based on the places students live, the schools they attend, the affluence of their parents, or their race. In the latter case technology once again exacerbates rather than mitigates inequities.

Responses to Equity Issues

Each of the equity issues we sketched above is serious, and each deserves attention. None of them is unique to technology, however. They thus require more general attention than the Center itself can provide. Our efforts must develop in conjunction with other efforts to reduce counterproductive inequities in education. We have already taken steps to foster this collaboration.

We envision three elements in the Center's work on these issues:

<u>First</u>, the highly focused nature of our work on math, science, and computer education is particularly well suited to helping teachers appropriately tailor their uses of educational technology to the students and subject matter involved without regard to irrelevant social attributes. We will study the differential responses of varied groups of students in our research with an eye to understanding and perhaps reversing current inequities in access, interest, and achievement. This, we believe, will lead to progress on the last two equity formulations articulated above.

<u>Second</u>, Over the long term, we plan to devote considerable attention to support issues affecting classroom implementation of our findings, including the equity-related support issues specified above.

<u>Third</u>, we plan to collaborate with several interested individuals and organizations to develop and fund research focusing on the pattern of resource inequities which exists today and its correlation with other forms of inequity. The object of this research will be twofold: to document the extent of these inequities, so that debate may move to their resolution; and to focus attention on the connections between distribution and effect patterns in educational technology and corresponding patterns in other areas of education. One essential step toward implementing these responses is to connect the Center more firmly with individuals and organizations sharing our concern for equity issues. This will involve both bringing new individuals into various existing Center projects and establishing new links between the Center and projects underway elsewhere.

Specific Research Program

Reaction to the specific research projects was generally positive. Two sorts of questions were raised by some respondents and are worth discussing here.

First, some commentators felt the research topics described in the preliminary agenda addressed subject matter encountered only by rather advanced secondary students. In reality, most of the projects concern material that should be taught early and often in a student's school career. In this draft we have taken care to explain the proposed research in ways that make clear the fundamental importance of its subject matter in the science and mathematics curriculum. Several of the individual projects are planned so that teaching and learning experiments can be conducted at various grade levels. These projects will compare the ways in which students of different ages respond to the material and may illuminate a sequence of teaching strategies appropriate for students as their abilities and knowledge advance.

Second, a few readers of the preliminary agenda asked for a fuller explication of the rationale for and coherence among the set of initial research projects. In the present draft, we have included fuller discussions on these points. We also have identified some of the cross-cutting themes which integrate the research projects both within and across domains.

At this point it seems neither necessary nor desirable to impose a more restrictive kind of coherence on the research projects. Each of the projects addresses a target of difficulty which is fundamental to the subject matter and to the curriculum of American schools. In subsequent years we will identify and study additional targets of comparable importance. As the research proceeds we anticipate that many sorts of relationships and recurring themes will emerge in our findings. We will make every effort to identify and analyze these themes in order to draw generalizable recommendations from our results.

A Final Note on Research, Technology, and Student Achievement

We deliberately omit from this agenda any claim that our research in and of itself will boost achievement test scores, either of students in general or of particular subpopulations. While we wholeheartedly embrace the goals of improving achievement in mathematics, science, and computer science, and of equalizing educational opportunity, we believe that neither research nor technology nor any combination of the two has the power to increase students' achievement.

We do believe, however, that research can help. It can deepen our understanding of subject matter and of students' misunderstandings, it can suggest ways that technologies may be used to improve instruction, it can guide the development of new software, materials, and techniques for us in the classroom, and over time it can help in a variety of subtle but powerful ways to change our assumptions about the limits and possibilities of education. It is through these contributions, we believe, that research on the educational uses of technologies can help teachers, students, and parents increase achievement in the nation's schools.

APPENDIX

ORGANIZATIONAL STRUCTURE AND MANAGEMENT

In accordance with the stipulations of the National Institute of Education, the Educational Technology Center performs five tasks: 1) develop and regularly update a research agenda, 2) conduct research on the uses of new technologies in science, mathematics, and computer education, 3) explore the educational potential of emerging technologies, 4) conduct graduate-level training, and 5) disseminate the findings and products of the Center's works to school practitioners, researchers, policy makers, and parents.

Successful performance of these tasks by the Educational Technology Center requires:

- a wide variety of resources with a diversity of perspectives, skills, and experience
- maximum interaction and collaboration among those resources
- continuing movement and dialogue between the worlds of research and practice
- capacity to respond flexibly to emerging issues, needs and opportunities
- an efficient and task-oriented operation

To these ends, we have designed an organizational structure and management plan based on the following characteristics and principles:

Each of the institutions participating in the Center has proven and acknowledged expertise and ongoing activities in the field so that each one brings to the Center a significant body of knowledge and experience and an extensive network of resources.

Institutional participation, though keyed to individuals is defined as a collaboration among institutions, rather than as contracts with individual consultants. Therefore the Center draws on the full array of institutional capabilities and resources.

While the Center operates with a clear division of responsibility by institution, mechanisms such as the Steering Committee and Working Groups ensure communication, participation, and integration across tasks and activities.

The Educational Technology Center consists of a consortium of organizations based at the Harvard Graduate School of Education. Each of the partners has responsibility for particular work on the five tasks described earlier.

Harvard Graduate School of Education serves as prime contractor and fiscal agent, and provides physical facilities for the Educational Technology Center. As prime contractor, Harvard is responsible for the overall management and direction of the Center. It also takes lead responsibility for assembling and overseeing teams to plan and conduct the research under Task 2; for research on word processors and interactive videodisc devices under Task 3; and for graduate level training under Task 4. As Co-Directors of the Center, Gregory Jackson and Judah Schwartz are responsible for Harvard's portion of the Center's work.

Other partners in the consortium operate under subcontracts to Harvard. They all participate in designing the Center's agenda and each sends a representative to the Agenda-Setting/Steering Committee. In addition, each partner takes responsibility for specific parts of the Center's scope of work.

Education Development Center (EDC) takes primary responsibility for coordinating the agenda-setting activities of Task 1, for research on voice recognition and reading under Task 3, and for New England based dissemination activities under Task 5. Charles L. Thompson, Director of EDC's Center for Learning Technology, is responsible for EDC's work on the Educational Technology Center.

Educational Testing Service (ETS) takes lead responsibility for the assessment of computer literacy activities in schools under Task 2 and for national dissemination under Task 5. Marlaine Lockheed, Senior Research

Sociologist in the Division of Education Policy Research and Services, is responsible for ETS's portion of the scope of work.

The Education Collaborative for Greater Boston (EdCo) facilitates the participation of school people in planning and conducting research under Task 2, helps coordinate training that responds to school practitioners' needs under Task 4, and assists in regional dissemination activities under Task 5. Judith Opert Sandler, Director of School Services at EdCo, is responsible for EdCo's work on the Center.

The four public school systems of Cambridge, Newton, Ware, and Watertown, Massachusetts each have subcontracts with Harvard. They participate in formulating research agenda and serve as prime sites for the collaborative school-based research activities conducted under Task 2 and 3. Representatives of these systems also help design and, in some cases, provide sites for training and dissemination activities under Tasks 4 and 5. The superintendent of each school system is a member of the Agenda-Setting Committee and is responsible for his system's work on the Center.

Children's Television Workshop and WGBH Educational Foundation contribute to planning and conducting research under Task 3 and, as appropriate, under Task 2. Their involvement focuses primarily on computer-augmented television. Kim Storey, Assistant Director of Educational Activities in the Department of Special Telecommunications Services, takes the lead for WGBH. Keith Mielke, President of Children's Computer Workshop, is responsible for CTW's work on the Center.

The Center also has an agreement with Interactive Training Systems (ITS). ITS provides the Center with access to state-of-the-art intelligent videodisc systems and works with Center personnel on exploring the educational applications of such devices. Harry Lasker, President of ITS, supervises ITS's work with the Center.